A holistic methodology *cum* database for wave energy exploitation: Implementation on the Galician coast (NW Spain)

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PhD thesis

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Abstract

The exploitation of the wave energy resource in a coastal region is based on the definition of two main aspects: the wave energy converter (WEC) and the location to install a wave farm. This decision making should be conducted on the basis of an accurate analysis of different factors, amongst which the power performance is fundamental. With this in view, in this thesis a holistic methodology far from the conventional approach is developed whose implementation in a coastal region produces a database containing the required information for accurately computing the power performance of any WEC at any coastal location. The methodology *cum* database is implemented on the Galician coast and a computer application developed so as to easily access and manipulate the large amount of information generated. As a result, the new decision-aid tool ***i*WEDGE** (intra-annual Wave Energy Diagram GEnerator) is available for the Galician coast, allowing the automatic reconstruction of annual and monthly high resolution characterization matrices at any coastal location, thereby providing the elements for a combined WEC-site selection.

Keywords: Methodology; Database; *i*WEDGE; Power performance; Characterization matrix; Energy bin; High resolution; Intra-annual variability.

Resumen

El aprovechamiento de la energía del oleaje en una región costera se basa en la definición de dos aspectos principales: el dispositivo convertidor de energía de las olas (WEC, wave energy converter) y la localización para instalar una planta de aprovechamiento undimotriz. Esta toma de decisiones debe ser realizada en base a un análisis de detalle de diferentes factores, entre los cuales el rendimiento energético es fundamental. Teniendo esto en consideración, en esta tesis se desarrolla una metodología holística que difiere en gran medida de los procedimientos convencionales, cuya implementación en una zona costera genera una base de datos que contiene la información necesaria para realizar estimaciones precisas del rendimiento de cualquier WEC en cualquier ubicación costera. La metodología *cum* base de datos se implementa en la costa gallega y se desarrolla una aplicación informática para acceder y manipular de modo sencillo la extensa información generada. Como resultado, la nueva herramienta de toma de decisiones ***i*WEDGE** (intra-anual Wave Energy Diagram GEnerator) está disponible para la costa gallega, la cual permite la reconstrucción automática de matrices de caracterización anual y mensual de alta resolución en cualquier localización costera, y por tanto proporciona los elementos para una selección combinada WEC-ubicación.

Palabras clave: Metodología; Base de datos; *i*WEDGE; Rendimiento energético; Matriz de caracterización; Intervalo de energía; Alta resolución; Variabilidad intraanual.

Resumo

O aproveitamento da enerxía da ondada nunha rexión costeira baséase na definición de dous aspectos principais: o dispositivo convertedor de enerxía das ondas (WEC, wave energy converter) e a localización para instalar unha planta de aproveitamento undimotriz. Esta toma de decisións deber ser realizada en base a unha análise de detalle de diferentes factores, entre os cales o rendemento enerxético é fundamental. Tendo isto en consideración, nesta tese desenvólvese unha metodoloxía holística que difire en gran medida dos procedementos convencionais, que ó ser aplicada nunha determinada rexión xera unha base de datos que contén a información necesaria para realizar estimacións precisas do rendemento de calquera WEC en calquera localización costeira. A metodoloxía *cum* base de datos aplícase na costa galega e desenvólvese unha aplicación informática para acceder e manipular de modo sinxelo a extensa información xerada. Como resultado, a nova ferramenta de toma de decisións ***i*WEDGE** (intraanual Wave Energy Diagram GEnerator) está dispoñible para a costa galega, a cal permite a reconstrución automática de matrices de caracterización anual e mensual de alta resolución en calquera localización costeira, e por tanto proporciona os elementos para unha selección combinada WEC-ubicación.

Palabras chave: Metodoloxía; Base de datos; *i*WEDGE; Rendemento enerxético; Matriz de caracterización; Intervalo de enerxía; Alta resolución; Variabilidade intraanual.

Preface

The exploitation of the wave energy resource in a coastal region is based on the combined selection of the most appropriate location and wave energy converter (WEC) for installing a wave farm. In this context, a large number of resource characterizations have been conducted over recent years. The greater part of these evaluations was focused on determining extreme and average wave conditions, along with characterizing in detail hot spots of interest. Despite all their interest, the resulting information does not provide the required elements for a combined WEC-site selection. For this purpose, it is necessary to bear in mind the final outcome of a wave energy resource assessment: to provide the elements for the reliable estimation of the performance of WECs at different locations of interest, based on which, an appropriate decision making can be performed.

In this thesis, a high resolution geospatial database covering the whole length of the Galician coast (NW Spain) is made available by defining and implementing a holistic methodology which is based on deepwater buoy data and spectral numerical modelling. Then, a MATLAB-based decision-aid tool is developed allowing the manipulation of the information generated and the automatic reconstruction of annual and intra-annual high resolution wave energy characterization matrices at any location within the Galician coast, or in other words, the required information for computing the power performance of any WEC-site combination of interest.

This thesis is structured in seven chapters as follows. First, Chapter I – *Introduction* provides an overall perspective of this work. Then, in Chapter II – *Objectives*, the final and intermediate objectives are presented. The three following chapters (Chapters III to V) correspond to original research articles published in peer-reviewed journals constituting the main body of this work. In Chapter VI – *General discussion,* an analysis of the results obtained in the preceding chapters

(Chapters III to V) is performed. Finally, in Chapter VII – *Conclusions*, the main contributions and findings, along with the planned future research, are presented.

This work has been conducted in the framework of the grant *Development of a Geospatial Database for the Exploitation of the Wave Energy Resource along the Galician Coast* funded by the Barrié Foundation, the project DPI2009-14546-C02-02 *Assessment of the Renewable Energy Resources* of the Ministry of Science and Innovation and the project *Online Application and High Resolution Management System for the Exploitation of the Wave Energy Resource in the Atlantic Region of Europe* supported by Iberdrola Foundation. The wave data have been kindly provided by Puertos del Estado.

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Symbols and abbreviations

Symbols

C	phase velocity [ms^{-1}]
C_f	capacity factor
C_g	group velocity [ms^{-1}]
C_θ	propagation velocity in θ-space [ms^{-1}]
C_σ	propagation velocity in σ-space [ms^{-1}]
E_b	energy provided by each bin [$MWhm^{-1}$]
E_o	monthly energy output [Whm^{-1}]
$H_{1/3}$	significant wave height [m]
H_{m0}	spectral significant wave height [m]
f	wave frequency [Hz]
f_p	peak wave frequency [Hz]
g	gravitational acceleration [ms^{-2}]
h	local water depth [m]
J	wave power per unit width [kWm^{-1}]
J_b	wave power per unit width of each bin [kWm^{-1}]
k	wave number [m^{-1}]
m_n	n-th spectral moment [m^2Hz^{-n}]
n	number of hours of a period considered [h]
N	wave action density [m^2Hz^{-2}]
O_b	occurrence of each each bin [h]
P_b	power output of a WEC for each energy bin [kW]
P_m	maximum power [kW]

S	spectral density [m^2Hz^{-1}]
t	time [s]
T_e	energy period [s]
T_p	peak period [s]
β	spectrum wave parameter
γ	peak enhancement factor
π	pi
ρ	seawater density [kgm^{-3}]
σ	relative frequency [Hz]
θ	wave direction [º]
θ_m	mean wave direction [º]
ζ	width of the spectral peak region

Abbreviations

AWS	Archimedes Wave Swing
GUI	graphical user interface
IF	impact factor
*i*WEDGE	intra-annual Wave Energy Diagram GEnerator
OTD	overtopping device
OWC	oscillating water column
SWAN	Simulating WAves Nearshore
WAB	wave activated body
WEC	wave energy converter
WEDGE	Wave Energy Diagram GEnerator

I

Introduction

Introduction

1. Motivation and scope of the thesis

Wave energy has emerged as one of the most powerful renewables with the potential to replace part of the energy fossil fuel generation (Bahaj, 2012). For this potential to be realized, it is necessary to develop efficient and reliable wave energy converters (WECs). As a result of the intensive research conducted over recent years to develop WECs (Babarit *et al.*, 2012; Falcão, 2010), the exploitation of this form of energy is approaching commercial viability.

The installation of a wave farm in a coastal region involves the definition of different aspects, amongst which the combined selection of the most appropriate location and technology is of major importance. In this vein, numerous resource evaluations have been conducted with the aim of installing a wave farm (e.g., Akpinar and Kömürcü, 2012; Iglesias and Carballo, 2010a; Lenee-Bluhm *et al.*, 2011; Rusu and Guedes Soares, 2012a; Smith *et al.*, 2013). The greater part of these evaluations was focused on determining the average and extreme wave conditions, along with identifying hot spots and characterizing in detail the wave resource at specific coastal locations. As a result, a fair amount of wave energy resource information has been made available throughout the most powerful coastal regions all over the world. Nevertheless, despite all its interest, this information does not provide the elements required for a combined WEC-site selection within a given coastal region, or in other words, it does not allow confident wave energy exploitation decision making. For this purpose, it is necessary to bear in mind the final outcome of a wave energy resource assessment: to provide the elements for the reliable estimation of the performance of any WEC at any location of interest in a coastal region, which in turn arises from the need for comparing different WECs at different locations and, on these bases, (i) to select the WEC that performs best at a given location, and (ii) to define the location within a coastal region or area allowing the greatest performance for a given technology.

The assessment of the power performance of a wave energy converter at a coastal site involves two tasks: (i) the characterization of the wave resource at the location in question, and (ii) the computation of the energy production and, on this basis, other performance parameters of interest. Unfortunately, these tasks are generally seen as disconnected and tackled as such; they are, however, deeply interrelated —so much so that they should be treated as two phases of the same procedure—. As a consequence, the way in which the greater part of the assessments have been conducted over recent years gives rise to a lack of the elements required for properly conducting this estimation.

The aforementioned limitation arises from the power performance of WECs largely depending on the characteristics of the wave climate at a specific location which stems from their efficiency —either expressed in terms of power output or percentage over the total energy available, as described by their power matrix— significantly varying with the wave conditions. Therefore, if accurate performance computations are to be conducted, the resource at a particular location of interest needs to be described by means of a characterization matrix (or energy diagram), examining the available energy and occurrence for the different wave conditions, expressed as joint combinations of the relevant spectral parameters, or the so-called energy bins. Then, the energy production of a given WEC at a site of interest would be the result of combining the device's power matrix with the location's characterization matrix. For this purpose, the characterization matrices should be computed following a specific procedure (Carballo and Iglesias, 2012; Henriques *et al.*, 2013) differing from the conventional one, designed to cover a significant percentage of the total energy resource available and to obtain a specific level of resolution of the energy bins (the same as that of the device's power matrix). On top of that, the wave energy resource may largely vary within short distances throughout a specific coastal region (e.g., Iglesias and Carballo, 2009b), meaning that the WEC providing the greatest performance is likely to vary depending on the location within the coastal area considered. In consequence, any resource assessment with a view to installing a wave farm in a coastal region should allow the accurate computation of the resource characterization matrix at any site of interest within the region, and thus the estimation of the performance of any WEC-site combination.

On the other hand, it has been shown that the regions with the largest wave energy potential usually exhibit a significant intra-annual variability of the resource (e.g., Neill and Hashemi, 2013; Sierra *et al.*, 2013), which may well lead to a considerable intra-annual variability in the power performance of WECs. Therefore, to compute the performance of a WEC at a coastal site exhibiting significant intra-annual energy variability on the basis of mere annual figures may conduct to ill-informed decision making. Instead, intra-annual matrices of the resource should be computed covering a temporal period (e.g., monthly, seasonal…) reflecting the variability of the resource. However, as stated, conventional resource assessments usually focus on average (or extreme) values, thereby providing little information regarding the intra-annual distribution of the resource. This results in the required information for generating intra-annual characterization matrices being currently only available at a limited number of coastal sites, usually those where a buoy has been in operation over large periods.

In this thesis, a geospatial database for the exploitation of the wave energy resource over the whole length of the Galician coast (NW Spain) is made available by developing and implementing a holistic methodology, based on deepwater buoy data and high resolution spectral numerical modelling, allowing the consideration of virtually the totality of the available resource. Then, a MATLAB-based decision-aid tool is developed so as to easy access and manipulate the database generated, allowing the automatic reconstruction of annual and intra-annual high resolution characterization matrices of the wave energy resource at any site within the Galician coast, and therefore the computation of the power performance of any WEC-site combination.

The methodology *cum* database herein presented is developed through a series of research articles, published in peer-reviewed journals, composing the main body of this thesis, each of them constituting a fundamental step towards the achievement of the final objective of this work: to make available a feasible and reliable procedure whose implementation in a given coastal region provides the required information for proper wave energy exploitation decision making.

2. Justification of the unity and coherence of the thesis

This thesis is structured in seven chapters as follows. First, the present Chapter (I – *Introduction*) provides an overall perspective of this work. Then, in Chapter II – *Objectives*, the final and intermediate objectives are briefly presented, the latter being defined according to the different tasks and coherent steps required so as to fulfil the proposed final objective. The three following chapters (Chapters III to V) correspond to respective publications in peer-reviewed journals constituting the main body of this thesis. Each of them represents a piece of research whose integration forms a whole through which a holistic methodology *cum* database for wave energy exploitation is developed. For this purpose, each of the publications deals with one of the three intermediate objectives as stated in Chapter II.

In Chapter III – *A high resolution geospatial database for wave energy exploitation*, a comprehensive methodology far from the conventional approach is presented so as to characterize the wave resource with the adequate resolution and accuracy in order to provide the elements for accurate performance computations of WECs. The implementation of this methodology is shown through a case study covering the whole Death Coast (Galicia, NW Spain). Then, a brand new MATLAB-based tool called WEDGE (Wave Energy Diagram GEnerator) is developed to easily access to the resulting database and automatically compute annual wave characterization matrices with the required resolution for performance computations purposes at any site throughout the Death Coast. Then, the interest of this methodology *cum* database is investigated, in particular with respect to the spatial resolution provided. This chapter has been published in *Energy* in 2014, journal indexed in the Journal Citation Reports with an impact factor, IF, of 4.844 (year 2014).

In Chapter IV – *Intra-annual wave resource characterization for energy exploitation: A new decision-aid tool*, the methodology *cum* database previously developed is extended in order to consider the intra-annual variations of the resource, and implemented in the same region, the Death Coast. In the same way, the MATLAB-based tool is also extended so as to allow the automatic computation of intra-annual characterization matrices. This new decision-aid tool is called *i*WEDGE (intra-annual Wave Energy Diagram Generator). Afterwards, the need for considering the intra-annual variations for a proper characterization of the resource in this region is further analysed. This chapter has been published in *Energy Conversion and Management* in 2015, journal indexed in the Journal Citation Reports with an IF of 4.801 (year 2015).

In Chapter V – *The intra-annual variability in the performance of wave energy converters: A comparative study in N Galicia (Spain)*, the aforementioned methodology *cum* database considering the intra-annual variations of the resource is implemented in the northern coastal region of Galicia. Next, the importance of considering the intra-annual variations for reliable performance computations of different WEC-site combinations is further investigated. This chapter has also been published in *Energy* in 2015 (IF=4.292, year 2015).

All in all, the original research articles composing the main body of this thesis are profoundly connected, each of them constituting a coherent step towards the fulfilment of the intermediate objectives of this research —which in turn lead to the achievement of the final objective— and therefore providing coherence and unity to this thesis.

Then, in Chapter VI – *General discussion,* an integrated analysis of the results obtained in the preceding chapters (Chapters III to V) is conducted so as to properly describe their significance within the general context of this work, thereby ensuring the reader's understanding of the present research as a whole. Finally, in Chapter VII – *Conclusions*, the main contributions and findings are synthetically presented along with the planned future research, part of which is currently under development.

II

Objectives

Objectives

The final objective of the present thesis consists in developing a comprehensive methodology allowing the generation of a database for accurately computing the performance of any WEC-site combination in a coastal region, and implementing it on the Galician coast, thereby providing the required information for proper wave energy decision making throughout this region. For attaining this final objective, the following intermediate objectives —each of them corresponding to a publication in a peer-reviewed journal which constitute the main body of this work— are established:

(i). To develop and implement in a coastal region of interest a methodology allowing the reliable computation of the annual performance of any WEC-site combination within the region.

Tasks involved: to develop a methodology whose implementation in a coastal region provides the required information for reconstructing the resource in the form of a high resolution annual characterization matrix at any location; to implement the methodology in a coastal region of interest in Galicia; to develop a computer application for easily accessing and manipulating the information generated; to analyse through a case study the need of the spatial resolution level provided.

(ii). To extend the methodology defined in (i) so as to consider the intra-annual variations of the wave energy resource, and implement it to the same coastal region.

Tasks involved: to extend the methodology defined in (i) so as to generate monthly characterization matrices at any location of interest; to implement the methodology in the same region as in (i); to adapt the computer application developed in (i) to the new dataset generated; to investigate through a case study the need for analysing the resource in terms of intra-annual characterization matrices.

(iii). To implement the methodology presented in (i) and extended in (ii) to another coastal region, showing the interest and functionality of the methodology *cum* database developed.

Tasks involved: to implement the methodology and develop the computer application previously defined to another coastal region within the Galician coast; to analyse through a case study the need for computing the intra-annual performance of different WEC-site combinations of interest.

III

A high resolution geospatial database for wave energy exploitation

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A high resolution geospatial database for wave energy exploitation

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ABSTRACT

The estimation of energy production of a given WEC (wave energy converter) at a given coastal site is the basis for correct decision-making regarding wave energy exploitation in a coastal region. Nevertheless, the procedure followed by the conventional approach to characterize the wave energy resource does not provide the required information to obtain an accurate estimate. In this work, this information is provided for the region with the greatest resource in the Iberian Peninsula, the Death Coast (NW Spain). For this purpose, a geospatial database is produced by using a methodology which involves the consideration of virtually the totality of the resource together with the implementation of a high resolution spectral numerical model. In addition, a Matlab-based toolbox called WEDGE (Wave Energy Diagram GEnerator) is implemented to access the database and automatically generate high resolution energy diagrams (or characterization matrices) of the wave energy resource at any coastal location within this region. In this way, a precise computation of energy production of any WEC at any site of interest can now be performed. Finally, the functionality of the database is shown through a case study of a recently proposed wave farm.

1. Introduction

The need for increasing the share of renewable energies to the total energy production has resulted in a growing interest in marine energies, amongst which wave energy has a great potential [1,2]. Wave energy is approaching viability as commercial power source as a result of the intensive research conducted over recent years to develop WECs (wave energy converters) [3]. This intensive research includes wave flume tests [4], 3D tank tests [5], the implementation of numerical models [4,6] or parametric studies [7]. On the other hand, numerous assessments of the available resource were also performed with the aim of installing a wave farm. They covered areas with substantial resource such as UK [8], Spain [9,10], the Black Sea [11,12], Portugal [13,14] or US [15]. The greater part of these assessments was focused on quantifying the total available resource in a particular region, making available valuable information about the characteristics of their wave climate and of the most appropriate areas for wave energy exploitation. Nevertheless, it is necessary to bear in mind the final outcome that a wave energy resource assessment should provide: the elements for the estimation of energy production of any WEC at any location of interest in a coastal region. This arises from the need for comparing the energy production of different WECs at different locations within a coastal region and, on this basis, i) to select the WEC that performs best at each location of interest and ii) to define the location providing the largest energy production for a given technology. In consequence, the estimation of energy production is of crucial importance to determine the viability of a project. Unfortunately, the way in which most of the assessments were conducted over the last years gives rise to a lack of the elements needed to properly conduct this estimation.

The energy production of a WEC at a particular coastal location is the result of combining the power matrix of the selected WEC with the energy diagram or characterization matrix at the location, representing the available energy and occurrence for the different wave height and period combinations [16]. Within the typical procedure, followed by most of the resource assessments conducted, there are two factors that represent a limitation when it comes to obtaining a coastal characterization matrix [16,17]: i) the number of wave conditions considered (normally no more than a few wave cases or a mere determination of the amount of kWm^{-1} available in an average year) and ii) the resolution of the wave energy characterization parameters. This provokes that the resulting coastal wave energy resource information cannot be used for describing the resource in the form of a characterization matrix with the adequate level of resolution (the same as that of the power matrix of the WEC) for accurate energy production computations.

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In this work, there is developed a high resolution geospatial database of the wave energy resource throughout the most powerful coastal region in the Iberian Peninsula, the Death Coast (NW Spain) (Fig. 1) [18], following a comprehensive procedure which differs from the conventional methodology (Section 2). As a result, the information required for reconstructing high resolution characterization matrices at any coastal site is now available. Furthermore, a Matlab-based toolbox is implemented, giving easy access to the information stored and allowing the automatic computation of the characterization matrices with the adequate resolution. In Section 3, the interest of the database is shown through the analysis of a recently proposed area for the installation of a wave farm in this coastal region. Finally, in Section 4, the main conclusions of the present work are drawn.

2. Database development

The present database has been developed by implementing a methodology composed of different steps. Given its complexity, in Fig. 2, a complete flow chart is presented with the aim of guiding and signposting the reader through this Section.

2.1. Characterization of the deepwater wave energy resource

The first step towards the assessment of the wave climate in a coastal region is to investigate its deepwater climate and, on this basis, to determine the wave conditions of interest. In the case of the Death Coast, it can be accurately characterized by the Vilán-Sisargas buoy located at approximately the middle point of the deepwater contour (Fig. 1). The dataset cover a period of around 14 years (1998–2012), comprising a total number of near 100,000 sea states with an hourly frequency.

For this purpose, the following spectral parameters of each sea state are computed from their hourly wave spectra: spectral wave height, H_{m0}, energy period, T_e, and mean wave direction, θ_m. H_{m0} is the spectral estimate of the significant wave height (or the average height of the highest 1/3 of the waves of a sea state), T_e the period of a sinusoidal wave with the same energy as the sea state, and θ_m the mean direction of the waves of the sea state.

They are computed respectively as follows [19]:

$$H_{m0} = 4(m_0)^{\frac{1}{2}}, \tag{1}$$

$$T_e \equiv T_{-10} = \frac{m_{-1}}{m_0}, \tag{2}$$

$$\theta_m = m_0^{-1} \int_0^{2\pi} \int_0^{\infty} \theta S(f,\theta)\, df\, d\theta, \tag{3}$$

where m_{-1} and m_0 represent respectively the minus first and zeroth moments of the wave spectrum, and $S(f,\theta)$ the spectral energy density which specifies how energy is distributed as a function of frequencies (f) and directions (θ). Next, the wave resource is characterized based on the probability distribution of the three aforementioned parameters (1–3) and using the concept of *energy bin* defined as trivariate intervals of significant wave height, energy

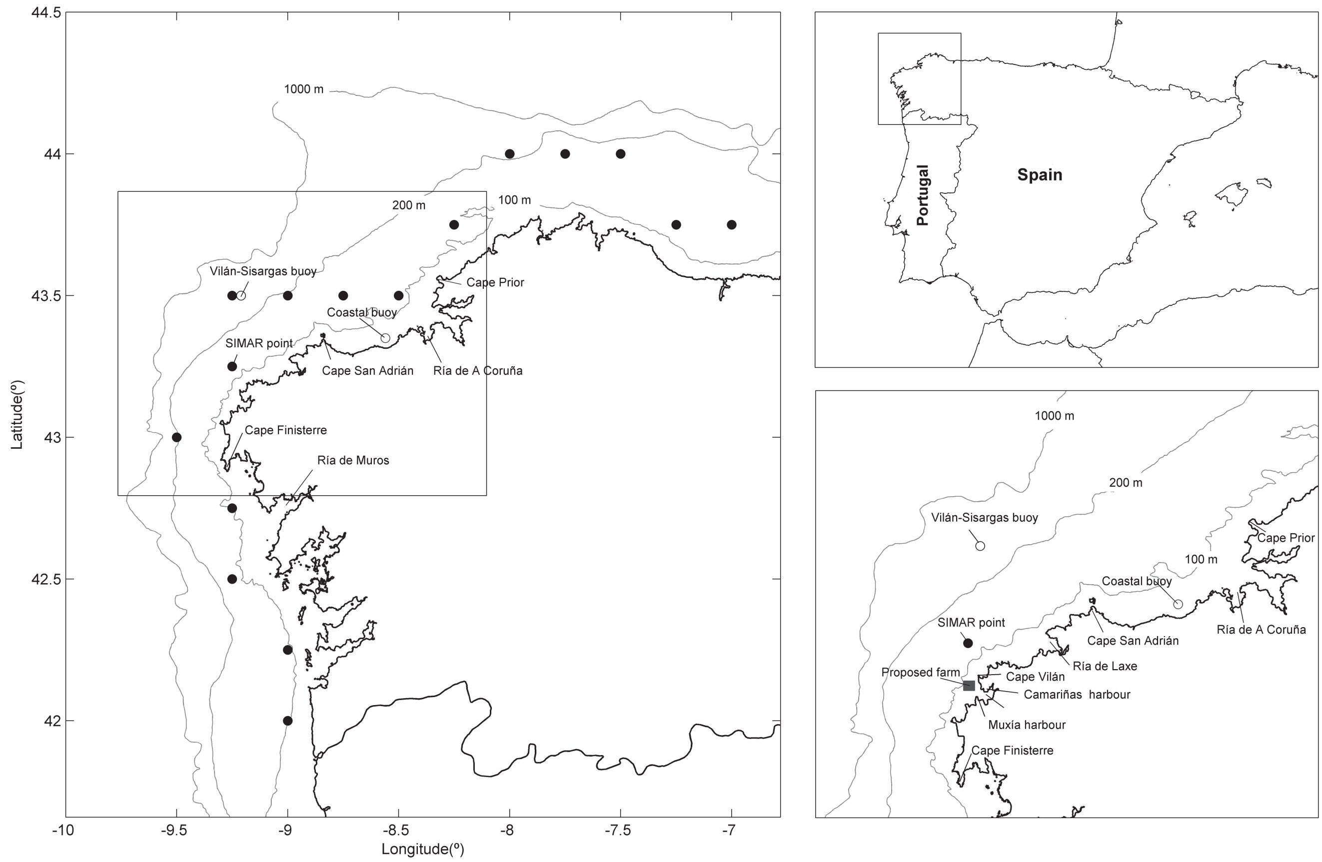

Fig. 1. Map of Galicia (left) in the NW of the Iberian Peninsula (above right), and the Death Coast region with a proposed area for a wave farm (below right).

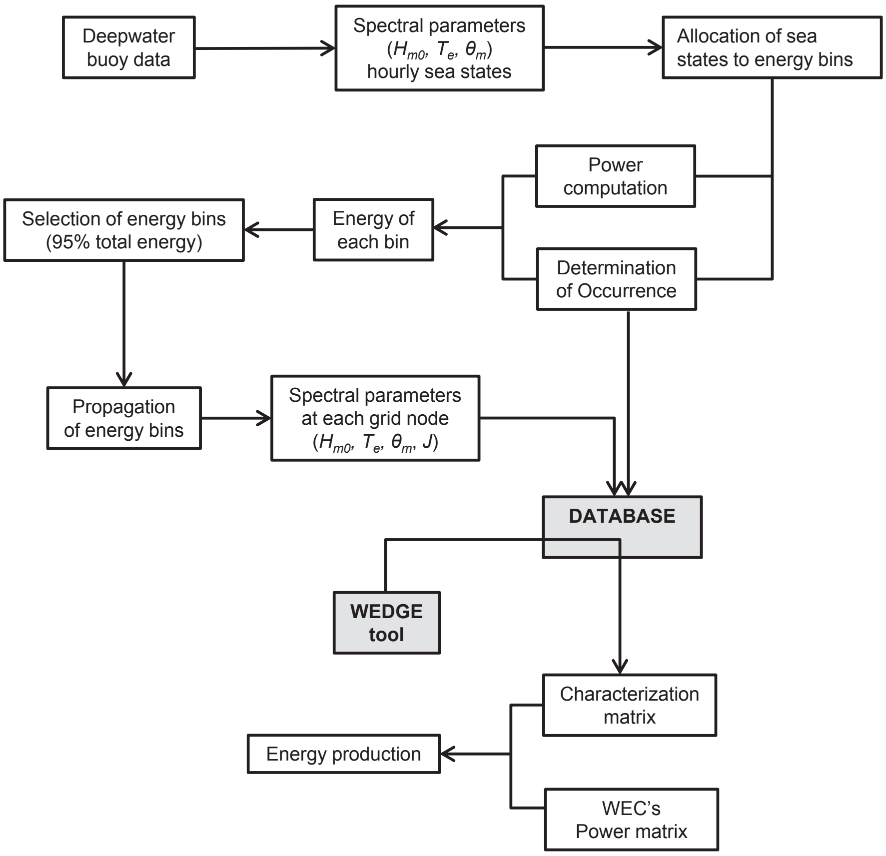

Fig. 2. Flow chart of the development of the database.

period, and wave direction [e.g. H_{m0} = 2–2.5 m, T_e = 8–8.5 s, θ_m = 326.25–348.75] [16].

A key aspect for a successful wave energy characterization is the selection of the adequate resolution or size of the energy bins. A concise way to present the predicted performance of a WEC is its power matrix – as the power curves in wind energy. It describes the WEC's performance for the different joint combinations of wave height and energy period. As stated, the actual energy that a WEC would produce at a site of interest is the result of combining its power matrix with the characterization matrix of the wave energy resource at that location. At present, two different power matrices can be provided by the different device developers: in terms of power output (Table 1) and in terms of efficiency (Table 2) for the different wave conditions (or energy bins). For energy production computations, the power matrix should be combined with the occurrence or with the total energy available of each energy bin specified by the characterization matrix depending on the information provided by the WEC developer (Table 1 or 2, respectively). Despite that at the moment there is no information being provided by device developers regarding how wave direction affects the performance of WECs (or in other words, it is assumed that, in the case of offshore and nearshore devices, they swing with the change in the wave direction or, in the case of onshore devices, the waves approach the shore parallel to the bottom contours as a result of the refraction process), the deepwater wave direction needs to be taken into account for an accurate resource assessment, as it greatly affects the wave propagation process and thereby the distribution of the resource giving rise to areas of high and low energy concentration.

On these grounds, it emerges that the resolution of the energy bins of the characterization matrices at a point of interest should be at least of the same level than that of the power matrix of the

Table 1
Power matrix of a WEC in terms of power output (kW).

H_{m0} vs T_e	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0
1.0	10	54	124	176	188	170	144	116	94	66	44	40
1.5	48	216	474	672	716	652	548	444	356	284	228	180
2.0	106	482	1050	1460	1538	1418	1210	986	794	634	508	350
2.5	190	854	1742	2232	2340	2212	1938	1668	1376	1116	898	646
3.0		1300	2516	2940	2900	2934	2598	2272	1936	1652	1376	964
3.5			2900	3000	3000	3000	2920	2888	2506	2142	1834	1300
4.0				3000	3000	3000	3000	3000	2900	2640	2350	1730
4.5					3000	3000	3000	3000	2940	2700	2460	1906
5.0						3000	3000	3000	3000	3000	2740	2134
5.5							3000	3000	3000	3000	2840	2470
6.0								3000	3000	3000	2940	2734

Table 2
Power matrix of a WEC in terms of efficiency (%).

H_{m0} vs T_e	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0
0.5	70.5	69.0	66.6	60.0	54.4	50.5	46.4	43.1	39.5	37.3	32.4	30.9
1.5		69.0	66.6	60.0	54.4	50.5	46.4	43.1	39.5	37.3	32.4	30.9
2.5			66.6	60.0	54.4	50.5	46.4	43.1	39.5	37.3	32.4	
3.5					54.4	50.5	46.4	43.1	39.5	37.3	32.4	
4.5						50.5	46.4	43.1	39.5	37.3	32.4	
5.5								43.1	39.5	37.3		

selected converter (they have to be combined), which means that the resolution of the deepwater characterization on which they are based should be also of the same level. Based on the information provided by the different wave energy device developers [20,21] the selected size of the energy bins are set to the highest resolution of a WEC's power matrix currently available: 0.5 m of H_{m0} and 0.5 s of T_e. Regards mean wave direction, in the present work intervals of 22.5° are used, which bring about an accurate description of the wave resource in NW Spain [16].

Once defined the resolution of the trivariate intervals, each of the hourly sea states in the dataset is assigned to the corresponding energy bin [e.g. H_{m0} = 3–3.5 m, T_e = 9–9.5 s, θ_m = 303.75–326.25°], and their wave power per unit width, J, computed according [22],

$$J = \frac{\rho g}{16} H_{m0}^2 C_g, \tag{4}$$

where ρ is the seawater density, g is the gravitational acceleration, and C_g is the group velocity, or the celerity at which wave energy is carried, which can be calculated as [23],

$$C_g = \frac{1}{2}\left(1 + \frac{2kh}{\sin h(2kh)}\right)\left(\frac{gT}{2\pi}\tan h(kh)\right) \tag{5}$$

where k is the wave number and h the local water depth. Now, the contribution to the total resource of each energy bin and its occurrence can be computed and used to produce a 3D characterization matrix. For clarity, Fig. 3(a) shows the omnidirectional representation (2D) of the 3D characterization matrix, with 0.5 m intervals of H_{m0} and 1 s of T_e (of a maximum of 0.5 s for clarity), with the colour plot representing the annual energy available (in MWh per meter of wave front) and the numbers, the occurrence (in hours per year) of each H_{m0} and T_e combination.

2.2. Selection and propagation of the relevant wave energy cases

The next step in the methodology is to propagate the most representative deepwater wave cases or energy bins – those providing the bulk of the energy. Although the conventional procedure is to consider a handful of study cases, recent studies have shown the importance of considering a high percentage of the total energy [16,17], which clearly will result in a more accurate estimate of the available resource and in consequence of energy production. In practice, it requires the consideration of a large number of energy bins, which means to propagate a large number of wave conditions and as a result a greater computational effort. In the present study, a sensitivity analysis (Table 3) is performed, showing the number of cases or energy bins that would be necessary to consider if a certain level of energy and time is to be achieved. It can be observed that, instead of propagating a great amount of cases so as to consider 100% of the available energy, the consideration of the 787 most energetic energy bins is enough to represent 95% of the resource (corresponding to 88.7% of the time). However, the consideration of a lower level of energy would not reduce significantly the number

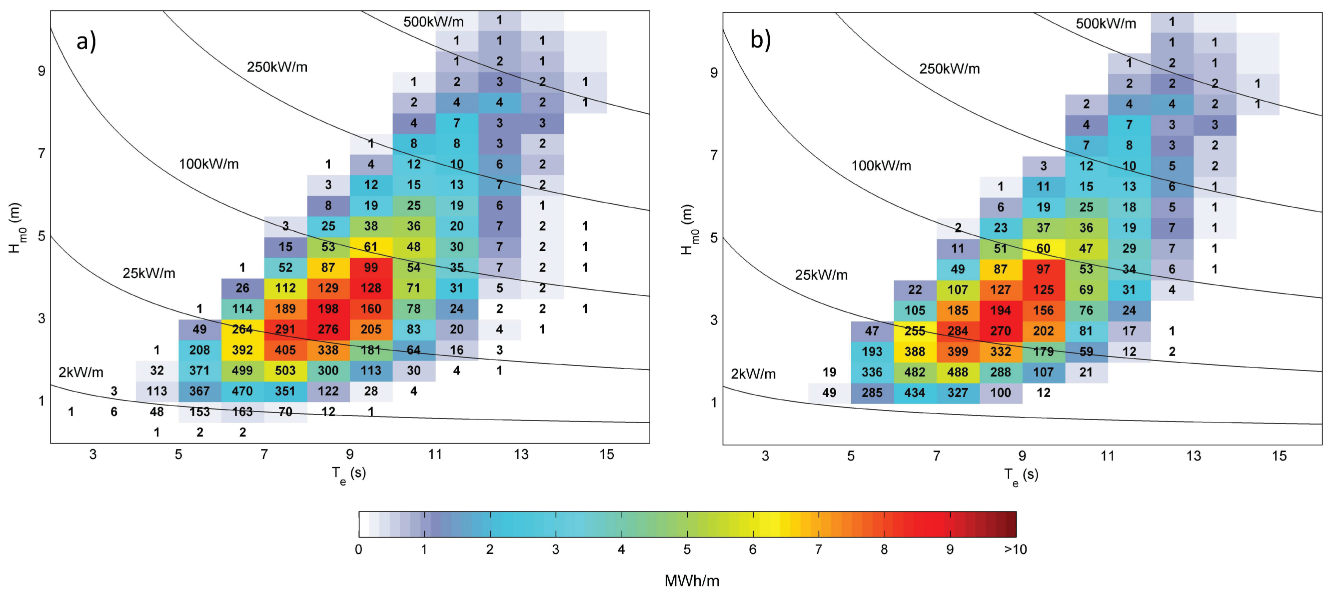

Fig. 3. Omnidirectional characterization matrix of the wave resource at the deepwater buoy considering 100% (a) and 95% (b) of the total amount of energy available. The colour plot indicates the total energy, and the numbers the occurrence in hours in an average year corresponding to each energy bin. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Sensitivity analysis (percentage of the total annual energy, % Energy, and percentage of the total annual time, % Time).

Number of energy bins	% Energy	% Time
182	50	42.8
381	75	66.8
622	90	83.5
787	95	88.7
1554	100	100

of cases to be propagated. The representation of the omnidirectional characterization matrix corresponding to 95% of energy (Fig. 3(b)) shows that the remaining 5% is mostly composed of two types of sea states: i) very low energetic sea states due to reduced wave heights and periods (sea states of under 1 m of H_{m0} are not considered) and ii) very powerful sea states with very low occurrence (extreme conditions). In both conditions, WECs do not operate; in the first case, they cannot operate due to the reduced wave height (Tables 1 and 2), and in the second case, WECs stop working to protect themselves (survival mode). This means that 95% of energy virtually represents 100% of the exploitable resource. Nevertheless, the consideration of a lower level of energy, may lead to not taking into account a large number of wave cases during which the WEC would operate. On this basis, the number of cases corresponding to 95% of energy of the total resource is retained in this work.

To propagate the selected wave conditions there is used the spectral model SWAN (Simulation WAves Nearshore) [24], which computes the evolution of the wave spectrum by solving the action balance equation. For this purpose a high-resolution grid is constructed (Fig. 4). The area covered by the grid is determined according to two prerequisites: i) the offshore boundary is located so deep that transformation processes have not yet influenced the wave field (deepwater condition) and ii) the lateral boundaries are distant enough so that any disturbance that may exist along them, cannot reach the region of interest.

The grid has a varying size decreasing from the deepwater contours towards approximately a 120 m water depth, the maximum depth at which offshore devices are expected to be deployed (and therefore the area of interest for wave energy exploitation). A key aspect to take into account is the fact that a strong variation in the available energy may exist in short distances (over a scale of hundreds of meters or even less), arising from a sudden variation of water depth. In other words, the characterization matrices within the coastal region may greatly differ over short distances. This variation should be properly modelled, for which the implementation of a high resolution grid is required. After a thorough analysis of the bathymetry of the area of study (Fig. 5) and considering previous wave energy studies in the region [19], the grid size in the area of interest (of under a depth of 120 m) is set to 200 m, much finer than that normally used following a conventional procedure. This results in a total number of grid nodes of 69,847.

Prior to propagating the selected energy bins, the model is validated by comparing the numerical results and buoy records. For this purpose, the model is forced with deepwater conditions recorded by the Vilán-Sisargas buoy covering a 14-day period (half-month), from 1.2.2011 to 15.2.2011, and the results compared with

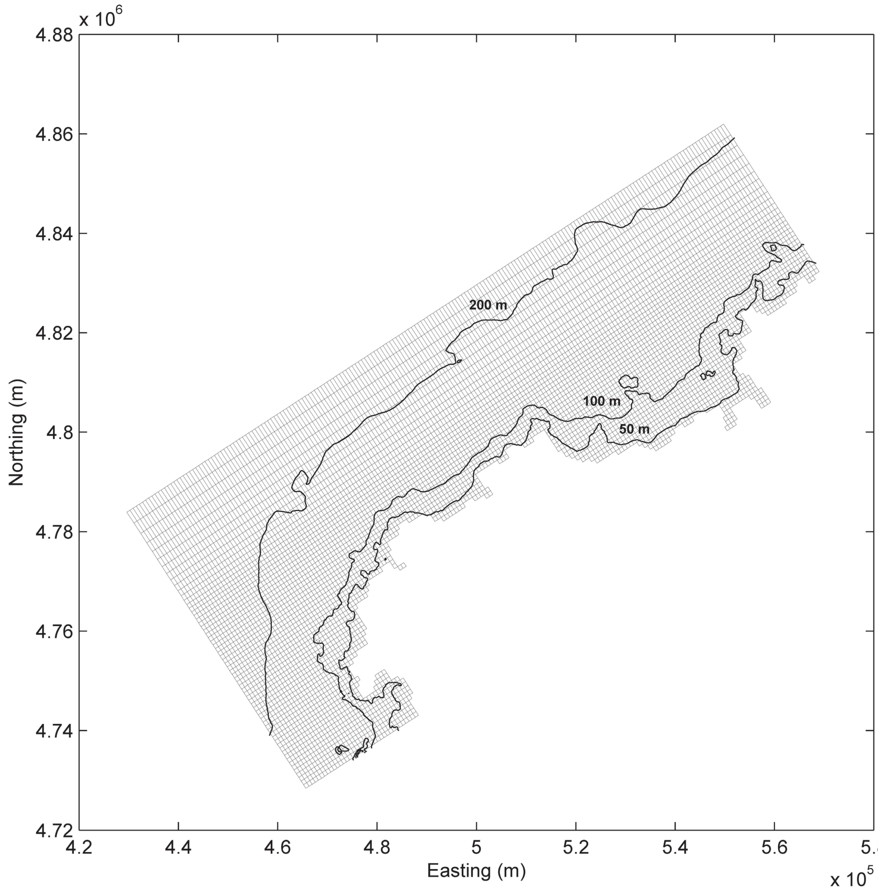

Fig. 4. High resolution grid for the spectral numerical model. For clarity, only one in three coordinate lines are shown.

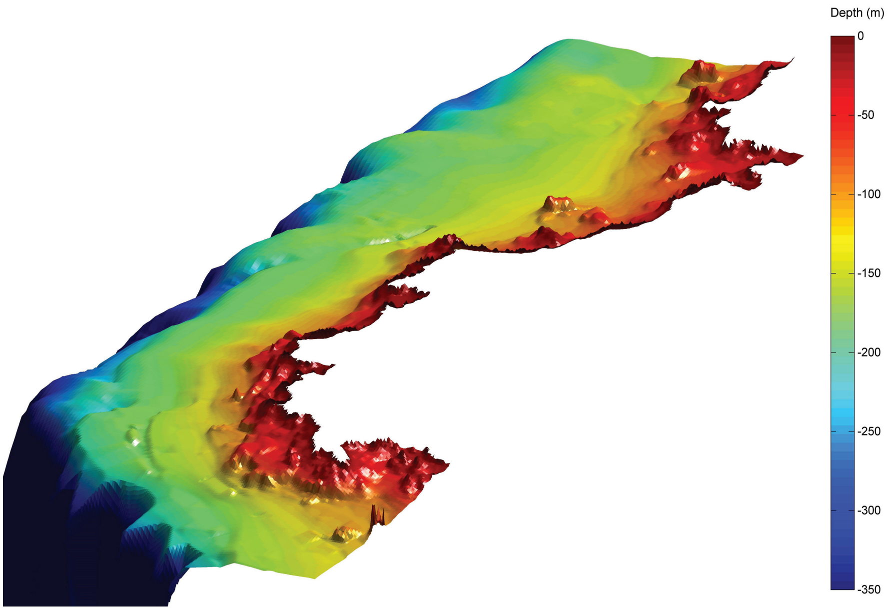

Fig. 5. 3D bathymetry of the Death Coast region.

hourly sea state records provided by a coastal buoy located at a 60 m water depth (Fig. 1). This period is selected insofar as it considers the whole range of wave conditions that a WEC can harness, including very powerful sea states. Excellent agreement is found between computational results and measurements (Fig. 6), obtaining a correlation coefficient of $R = 0.924$ and $R = 0.917$ for wave height and wave power, respectively.

Once validated the numerical model, the selected wave cases (787 energy bins) are propagated towards the coast. The wave conditions prescribed at the open ocean boundary representing each energy bin are set to those providing the average energy of the corresponding bin and the remaining spectral parameters defined following previous wave resource studies in the region [16]. For instance, in the case of the energy bin [$H_{m0} = 3$–3.5 m, $T_e = 9$–9.5 s, $\theta_m = 303.75$–$326.25°$], the parameters propagated are: $H_{m0} = 3.269$ m, $T_e = 9.25$ s, $\theta_m = 315°$.

2.3. Wave energy resource at a particular location

This step of the methodology consists in obtaining the modified wave parameters at any site within the Death Coast (grid nodes of the computational domain) with a view to provide the elements allowing the computation of energy production. For this purpose, after running the model, the spectral parameters H_{m0}, T_e, and θ_m at each grid node are obtained for each wave condition propagated and the wave power is computed according to [25]:

$$J = \rho g \int_0^{2\pi} \int_0^{\infty} S(f,\theta) C_g(f,h) df d\theta. \tag{6}$$

Subsequently, the energy associated with each wave field is obtained from its wave power and their probability of occurrence

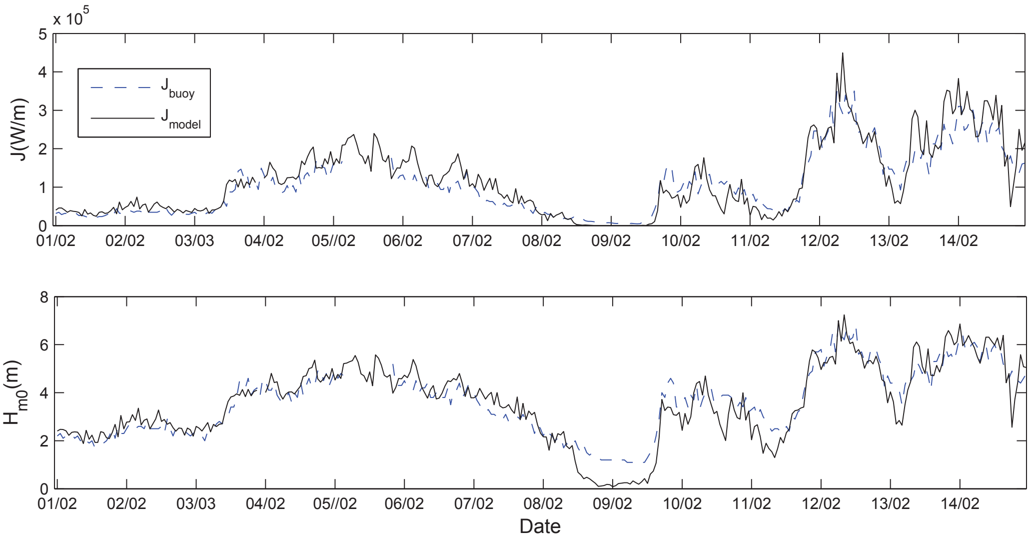

Fig. 6. Wave power (above) and spectral wave height (below) computed by the numerical model and recorded at the coastal buoy location.

from the characterization of the deepwater wave resource (although the wave field is transformed as it propagates from deepwater to the shore, its probability of occurrence is conserved). As a result, the same spectral parameters of interest at the deepwater buoy are now available at any point of the computational grid. Therefore, the wave resource at any location within this region can be reconstructed in the form of a characterization matrix (with the same resolution of energy bins as the deepwater characterization, and spatial resolution as the computational grid), following the same procedure explained in Section 2.1.

2.4. A Matlab-based toolbox for characterization matrix generation

The final step of this work is to develop a toolbox capable of reading the information stored in the database, and automatically reconstructing the wave energy resource, in terms of an energy diagram or characterization matrix with the appropriate resolution at any point within the Death Coast. Therefore, any device developer, policy maker, researcher or stakeholder will be able to easily compute the energy production of any WEC at any location of interest.

For this purpose, it would be enough to compute and store the figures corresponding to the total energy available and the number of hours of occurrence of each energy bin at each grid node (the information included in the characterization matrix) and then develop a programme to handle this information. The problem lies in the fact that the storage of 69,847 characterization matrices (number of grid nodes) represents an enormous amount of data to be stored (it would occupy a great part of a personal computer hard disk) which, in addition, would considerably slow down (or even impede) the functioning of the programme. With this in view, a set of programmes written in MATLAB, which can directly read the information resulting from the 787 numerical propagations and automatically reconstruct (in real time) the characterization matrices, was developed without the need for storing a huge amount of data. The result is the toolbox **WEDGE (Wave Energy Diagram GEnerator)**, a package of routines which works as follows. First, the toolbox is invoked by typing **WEDGE** in the Matlab Command Window (Fig. 7). Then, the user is asked to define the resolution of the energy bins of the characterization matrix (obviously, the maximum resolution available is $H_{m0} = 0.5$ m, $T_e = 0.5$ s in case of considering an omnidirectional matrix), which should be of the same level as that of the power matrix of the device used for energy production computations. Next, the toolbox asks for the location of interest where the characterization matrix is to be computed. This can be done in two different ways: i) by introducing manually the spatial coordinates or ii) by using a GUI (graphical user interface) specially designed for this purpose. If the user

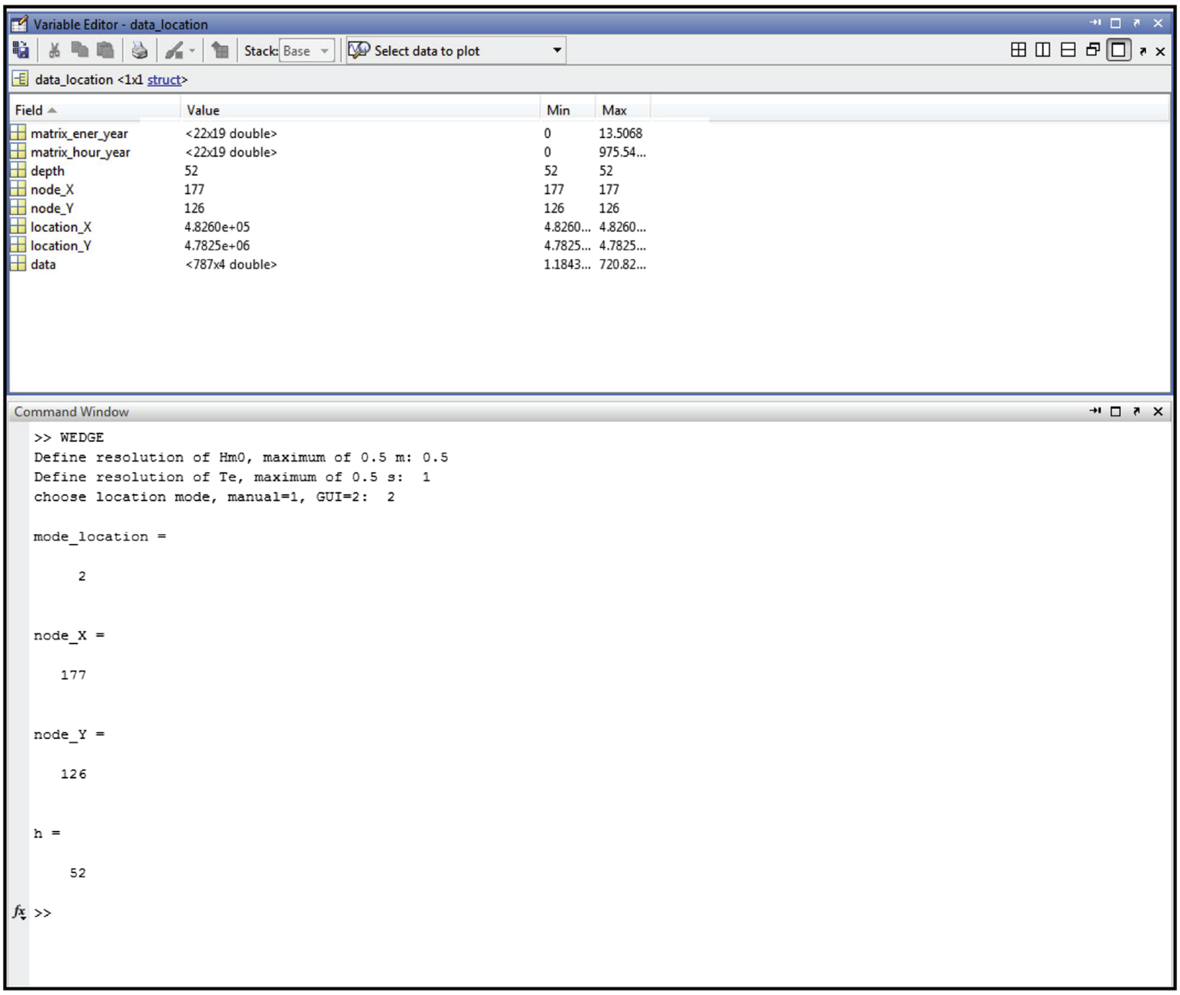

Fig. 7. Toolbox as it is shown within the Matlab interface. Below (Command Window), the options selected by the user to obtain the characterization matrix at a point of interest are shown; above (Variable Editor), the data contained in the variable *data_location_interest* are also shown.

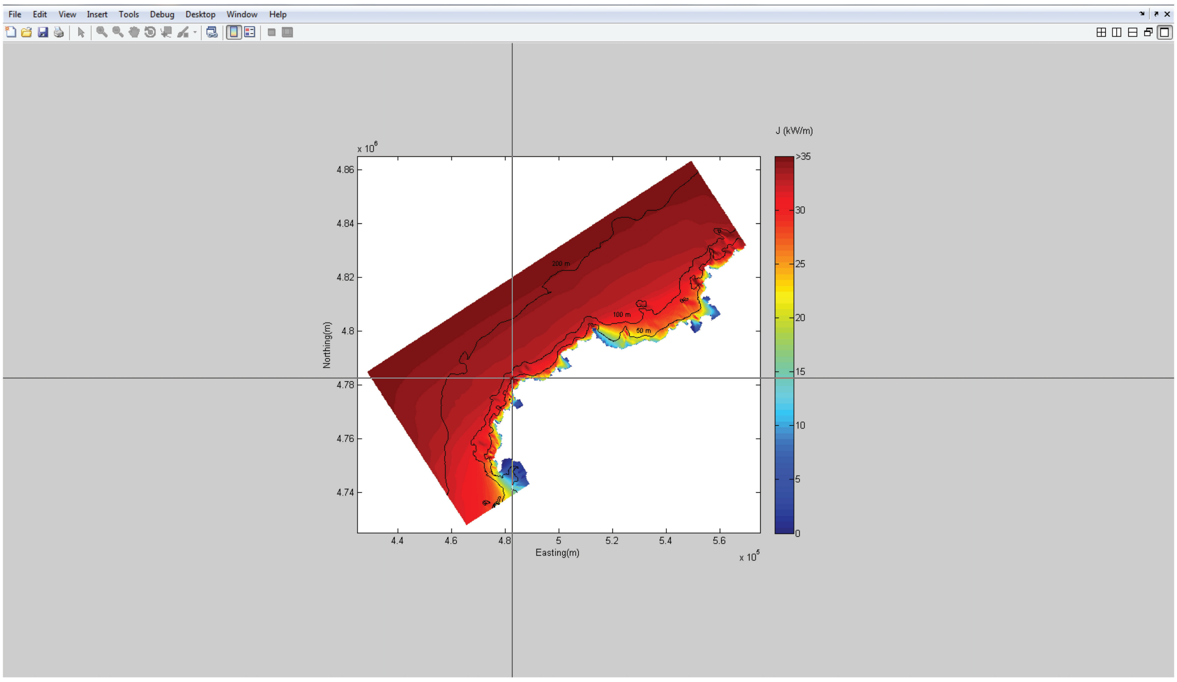

Fig. 8. GUI for selecting a point of interest where the characterization matrix is to be computed.

chooses the second option, a map of the average power available including the bathymetric isolines is automatically plotted on which a pointer is available for the interactive selection of the desired location (Fig. 8). When the user defines a location, the code finds the closest grid node (node_X and node_Y in Fig. 7). Afterwards, the information at this node corresponding to the spectral parameters stored resulting from the 787 wave cases propagated, as well as the number of annual hours of occurrence of each wave case, are read and used by the toolbox to reconstruct the corresponding energy diagram (characterization matrix) with the appropriate resolution (Fig. 9). As stated before, the computations are performed in real time, a process which only takes a few seconds. The total energy and the number of hours of occurrence corresponding to each energy bin of the characterization matrix (*matrix_ener_year* and *matrix_hour_year* variables, respectively), together with other data of interest are automatically stored within the structured variable *data_location* (Fig. 7). Thereby, the user can select the required information for energy production calculations depending on the characteristics of the device's power matrix (Table 1 or 2).

It is important to note that the energy bins of the characterization matrix showed (Fig. 9) correspond with a bivariate distribution of the H_{m0} and T_e in which the θ_m is neglected (omnidirectional matrix). This stems from the fact that, as stated in Section 2.1, the power matrices currently provided by device developers – with which the characterization matrices have to be combined in order to compute the energy production – are also omnidirectional. Nevertheless, the wave direction is taken into account throughout the development of the database; in particular, the numerical model computes the modification of the wave direction of each energy bin in their propagation from deepwater towards the coast, and the results are stored within the database together with the remaining spectral parameters. Thus, the user can use the database to generate 3D characterization matrices (including wave direction), if the information related to the variation of the WEC's performance with the variation in wave direction is provided in the future.

Finally, some regions of interest for wave energy exploitation have been shown to exhibit a significant seasonal or even monthly wave climate variability [26–31]. In this case, in addition to the total energy production, intra-annual wave resource information should be analysed for computing other parameters of interest providing relevant information for the proper configuration of WECs (e.g. installed capacity) [16].

3. Case study

The interest of the present database, as previously explained, lies in two facts. In first place it has been shown in Section 2 the need for describing the resource in the form of a characterization matrix with the appropriate resolution of energy bins, given that

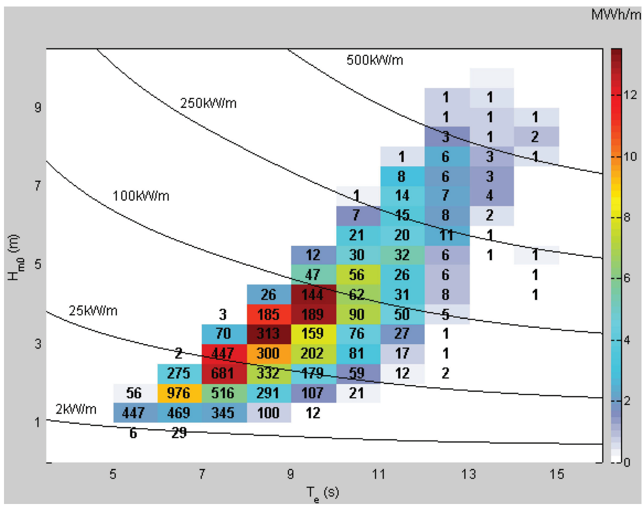

Fig. 9. Characterization matrix automatically generated at the location selected with the GUI in Fig. 8.

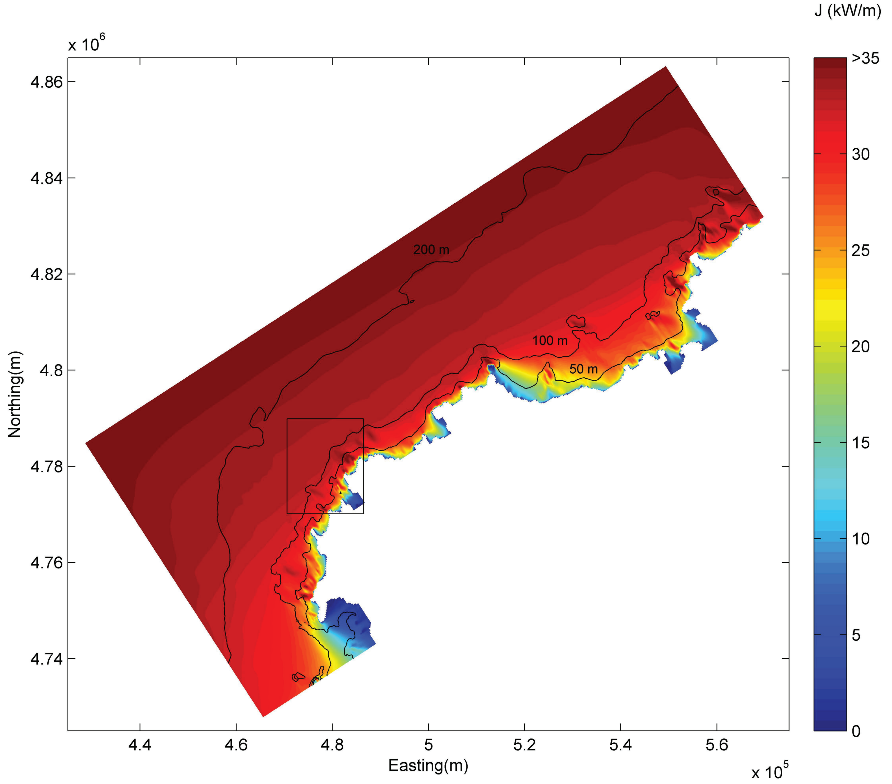

Fig. 10. Average wave power [kW/m] throughout the Death Coast. The rectangle indicates the coastal zone within which the variations in the wave energy resource are analysed (Fig. 11).

the WEC's power matrix with which it has to be combined has also a specific bin resolution. The current lack of this information is solved for the Death Coast by means of the present database, which is capable of generating characterization matrices with the same resolution as the maximum resolution of the WECs' power matrices. In second place, the irregular bathymetry of some areas may cause abrupt changes in the spatial distribution of the resource, and therefore the characterization matrices within the coastal region may greatly differ in short distances. Thus, this resource variability should be properly described for accurate wave energy production computations.

In this section, the importance of the spatial resolution provided by the present database for properly describing the spatial variability of the wave energy resource, is analysed through a case study. The available wave power in this region has been previously studied, and several hot spots identified and proposed as possible areas for wave energy exploitation [18]. One of these areas is of special interest, due to its being located next to two harbours (Fig. 1), and thus selected for further analysis with the database.

Prior to this work, the only data available for energy production computations in this region were those corresponding to the SIMAR-44 dataset (black circles in Fig. 1) (in addition to buoy data), composed of hindcast wave data covering a 44-year period (1958–2001) with a 3-h frequency. These dataset were obtained using the WAM third generation spectral model forced with wind fields provided by the REMO atmospheric model within the HIPOCAS project [32] which in turn was forced with data resulting from global atmospheric reanalysis computed by the U.S. National Center for Environmental Prediction. Despite their constituting a set of data with valuable information regarding the wave climate, it may occur that they do not provide accuracy when computing the energy a WEC would produce at a specific coastal location of interest. In the present case study, the closest SIMAR point to the proposed area for wave energy exploitation (Fig. 1) is located at a distance of more than 20 km and, more importantly, at an utterly different depth. Therefore, the resource provided by SIMAR point is expected to be quite different from that within the area of interest, which in turn would lead to significant inaccuracies when computing the energy production in the proposed area, should SIMAR characterization matrix be used for this purpose. In addition, SIMAR dataset does not provide information related to the T_e; instead, the peak period, T_p has to be transformed into T_e assuming a specific spectrum, leading to a less precise estimation of the energy contained in each energy bin.

In order to accurately define the deviation of the wave resource between the closest SIMAR point and within the area proposed for a wave farm, the characterization matrices at SIMAR location and at three locations within the area of interest are compared (Figs. 10 and 11). In the case of the SIMAR point the characterization matrix (Fig. 12) is computed assuming that $T_e = 0.9T_p$ following previous studies [16]. In addition, it has been stated that in areas with irregular bathymetry, as it is the case, changes in the available wave energy resource could exist over scales of hundreds of meters or even less, meaning that the energy that could be produced at different locations within the proposed area could greatly differ. On this basis the three locations selected (A,B,C) are separated by a distance of less than 500 m (Fig. 11) and their characterization matrices computed by means of the database (Fig. 13). For clarity and comparison purposes, the resolution of the energy bins is set to $H_{m0} = 0.5$ m and $T_e = 1$ s (of a maximum of $T_e = 0.5$ s).

It can be observed that there exist quite important differences between the wave energy resource at the SIMAR point and the

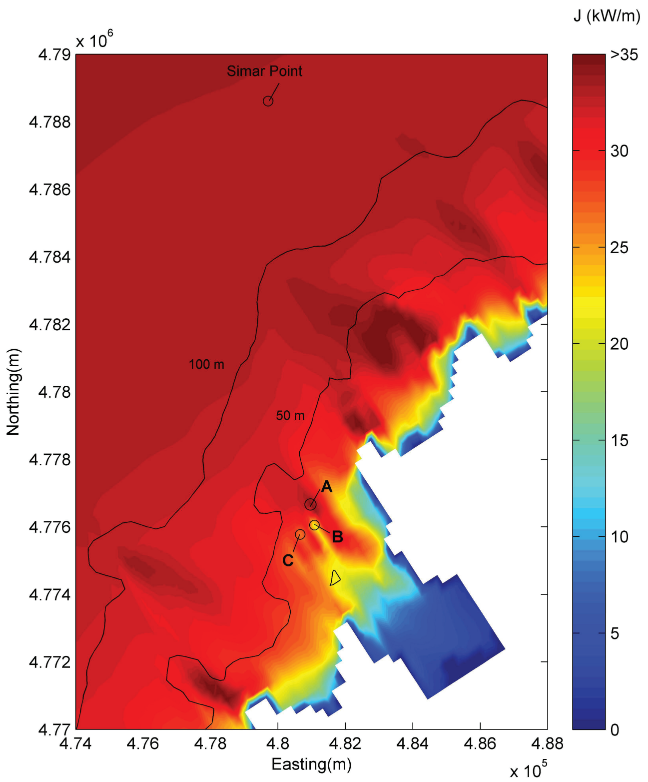

Fig. 11. Average wave power map of the coastal zone marked in Fig. 10 with the locations (A, B, C and SIMAR) at which the characterization matrices are reconstructed.

proposed area, as it could be expected for the distance and different depth. In addition, when comparing the characterization matrices at the three points (A, B, C) within the area of interest, significant deviations, although of less importance, are again observed. The major difference consists in that, whereas at point A the bulk of the energy is distributed over a wide range of H_{m0} and T_e, at points C and especially B, it is concentrated within a reduced number of energy bins. Obviously, the significant dissimilarities in the resource will lead to significant deviations in the estimation of the actual energy a WEC would produce.

4. Conclusions

A correct decision-making regarding wave energy exploitation should be based on an accurate knowledge of the different factors affecting its exploitation. Amongst them, the estimation of energy production of a WEC at a location of interest is of key importance. In this paper, a comprehensive procedure, far from the conventional approach, is implemented in the Death Coast (NW Spain) with the aim of developing a geospatial database of the wave energy resource providing the required information for conducting this estimation with accuracy and reliability throughout this region.

First, the deepwater wave energy resource is characterized based on a large dataset of spectral buoy records and following the *energy bin* concept, or trivariate intervals of significant wave height, energy period and mean wave direction. Furthermore, in contrast with the conventional approach which considers only a handful of study cases and a limited resolution of the energy bins, this work covers 95% of the total energy (which in practice represents virtually 100% of the exploitable resource) with a resolution of 0.5 m of wave height, 0.5 m of period and 22.5° of wave direction. This resolution is shown to be enough to characterize the resource with a view to energy production calculations. Next, a high resolution numerical model (grid spacing of 200 m) is implemented and a total of 787 wave cases (those corresponding to 95% energy level) are propagated.

Finally, a Matlab-based toolbox called WEDGE capable of accessing the database and of reconstructing the wave energy resource at any point in the Death Coast is implemented. It allows the selection of any location (resolution of 200 m) and the computation of its characterization matrix with the aforementioned size of energy bins. Once computed the matrix, the relevant

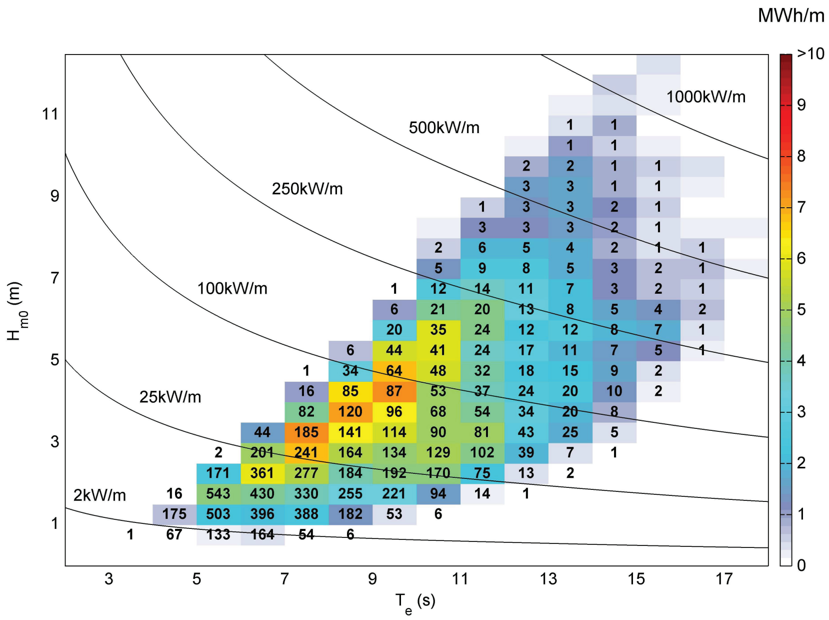

Fig. 12. Characterization matrix at the SIMAR point closest to the proposed area for a wave farm. The colour plot indicates the energy available, and the numbers the occurrence in hours in an average year corresponding to each energy bin. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

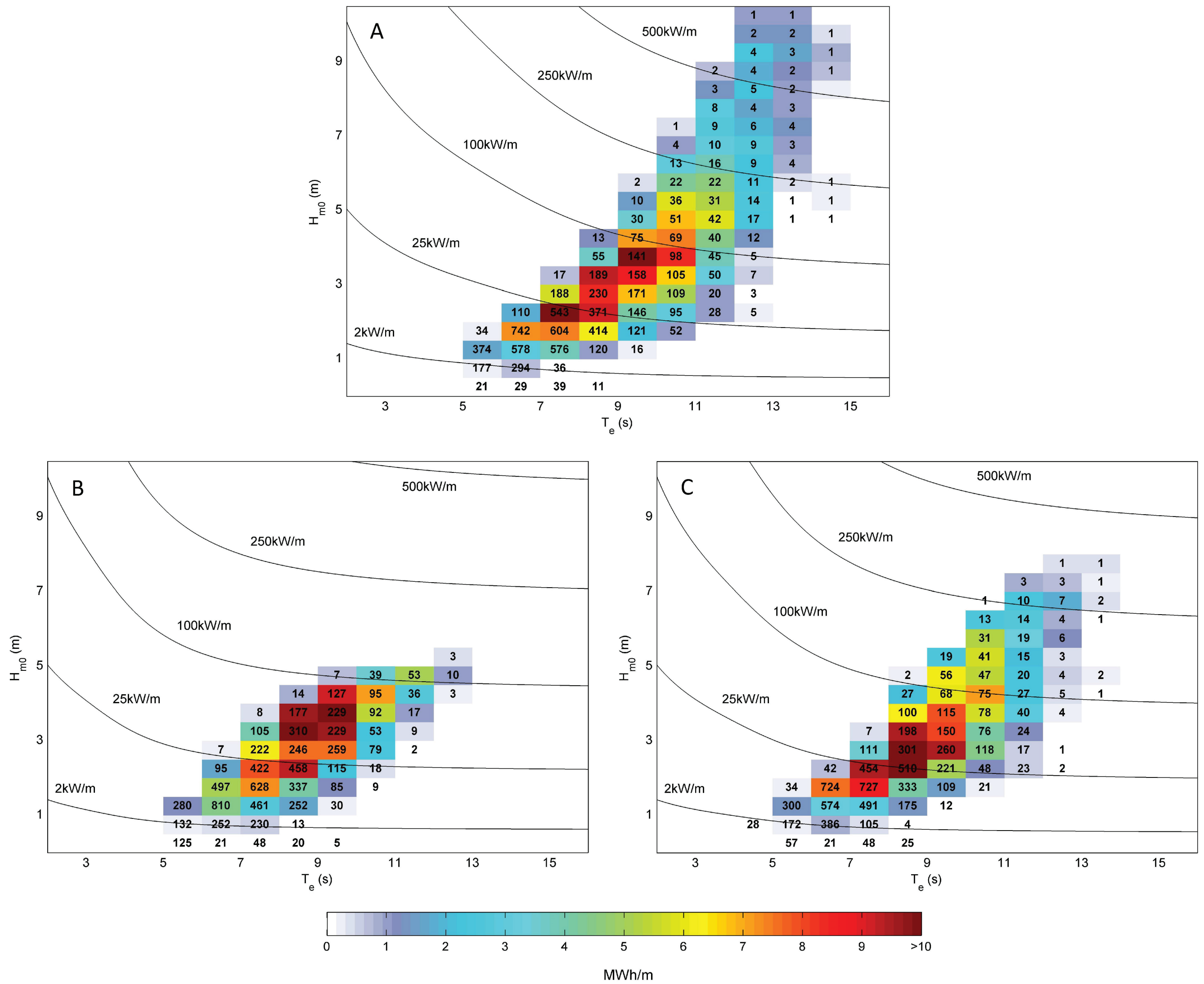

Fig. 13. Characterization matrices of the wave resource at points A, B, C within the proposed area for a wave farm. The colour plot indicates the energy available, and the numbers the occurrence in hours in an average year corresponding to each energy bin. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

information is automatically stored and thereby, it suffices to combine it with the corresponding information contained in the WEC's power matrix to determine the energy production at the desired location.

The interest of this database, and in particular of the spatial resolution provided, is further investigated by means of a case study, a recently proposed wave farm in the Death Coast. Several wave characterization matrices are generated and compared: i) a characterization matrix at the SIMAR point closest to the proposed area for the wave farm, which is at a distance of more than 20 km (the only wave resource dataset available prior to the present work), and ii) three characterization matrices at three different locations within the proposed area, separated by less than 500 m. It is shown that, first, in the present case study SIMAR dataset are not valid for energy production computations and further information is necessary, and second, a high resolution spatial database (more than 500 m) is required in such regions of irregular bathymetry as the Death Coast.

In summary, in this work there is developed a database of the wave energy resource throughout the Death Coast, NW Spain. The database allows the generation of high resolution characterization matrices at any coastal site and thus providing accuracy and reliability in the computation of the energy that any WEC would produce at any location of interest. Although the present database is currently only available for this region, the procedure developed in this work could be used to produce a database in any other coastal region in which long-term deepwater data are available.

In future work, the database will be extended so as to produce additional information of interest for wave energy exploitation. In particular, it will be extended in order to compute intra-annual characterization matrices providing relevant information for the proper configuration of a WEC at a specific location of interest.

Acknowledgements

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Renewable Energy Resources of the Spanish Ministry of Science and Innovation.

List of symbols

H_{m0}	significant wave height [m]
T_e	energy period [s]
θ_m	mean wave direction [°]
m_n	n-th spectral moment [m^2Hz^{-n}]
S	spectral density [m^2Hz^{-1}]
θ	wave direction [°]
f	wave frequency [Hz]
J	wave power per unit width [kWm^{-1}]
ρ	seawater density [kgm^{-3}]
g	gravitational acceleration [ms^{-2}]
C_g	group velocity [ms^{-1}]
k	wave number [m^{-1}]
h	local water depth [m]
T_p	peak period [s]

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IV

Intra-annual wave resource characterization for energy exploitation: A new decision-aid tool

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Intra-annual wave resource characterization for energy exploitation: A new decision-aid tool

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ABSTRACT

The wave energy resource is usually characterized by a significant variability throughout the year. In estimating the power performance of a Wave Energy Converter (WEC) it is fundamental to take into account this variability; indeed, an estimate based on mean annual values may well result in a wrong decision making. In this work, a novel decision-aid tool, *i*WEDGE (intra-annual Wave Energy Diagram GEnerator) is developed and implemented to a coastal region of interest, the Death Coast (Spain), one of the regions in Europe with the largest wave resource. Following a comprehensive procedure, and based on deep water wave data and high-resolution numerical modelling, this tool provides the monthly high-resolution characterization matrices (or energy diagrams) for any location of interest. In other words, the information required for the accurate computation of the intra-annual performance of any WEC at any location within the region covered is made available. Finally, an application of *i*WEDGE to the site of a proposed wave farm is presented. The results obtained highlight the importance of the decision-aid tool herein provided for wave energy exploitation.

1. Introduction

Wave energy has emerged as one of the renewables with the capacity to contribute large amounts of energy to society [1]. For this purpose, different types of Wave Energy Converters (WECs) are close to achieving a commercial stage [2–4]. There exist a wide variety of WECs which can be classified based on different criteria, such as the distance to the shoreline and water depth, the size and orientation relative to the waves, and the principle of operation. Regarding the principle of operation, three main types can be distinguished: overtopping devices (OTDs) [5], oscillating water columns (OWCs) [6,7] and wave activated bodies (WABs) [8].

Overall, the selection of the suitable converter depends on different aspects, amongst which the magnitude and distribution of the available resource is of major importance. Therefore, along with the development of WECs, a good climate description is crucial for a proper decision making and planning of the resource exploitation. In particular, the distribution of the energy resource in a region is the basis for the combined selection of the most appropriate location and type of WEC, as well as to define its optimum configuration. Furthermore, the optimum configuration of a WEC should be defined through an exhaustive analysis of different power performance parameters of a selected WEC-site combination. This is of special interest in the case of islands or when a specific energy demand is to be supplied [9–13] and energy storage is required [14]. In this vein, it is important to bear in mind that the information required at a given coastal location for WEC performance computations is a characterization matrix (or energy diagram) describing the available energy and occurrence of the different combinations of the relevant spectral parameters or *energy bins* [15]. This information is then combined with the power matrix of the WEC in question to compute the various performance parameters.

In addition, it has been shown that the regions with the greatest wave energy potential exhibit an important intra-annual variability of the resource [16,17] which may lead to a significant intra-annual variability in the power performance of WECs. Thus, to compute the power performance of a WEC at a coastal site exhibiting significant intra-annual energy variability on the basis of mere annual figures may lead to an incorrect decision making regarding the definition of the wave farm configuration. Instead, intra-annual matrices of the resource covering a period (e.g., monthly, seasonal…) capable of reflecting the existing variability of the resource should be generated at the location of interest. In spite of this, regional assessments usually focus on averaged

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resource values, giving little information regarding its intra-annual distribution. As a result, the required information for generating intra-annual characterization matrices is currently only available at specific coastal sites, normally those where a buoy has been in operation during large periods, which are not necessarily those where wave energy exploitation is being considered. At present, numerical modelling is also being used to generate large wave datasets which could be used for the same purpose [18,19]. In the case of the North Atlantic Region, the dataset recently provided within the HIPOCAS project [20] is of special interest. It consists of 44 years (from 1958 to 2001) of hindcast wave (and wind) data with a three-hourly frequency obtained after running the WAM model, which in turn was forced with data resulting from the regional atmospheric model REMO. However, it has been shown that the wave energy resource may show significant variations in short distances (even less than hundreds of meters). Therefore, the spatial resolution provided in this dataset, $30' \times 30'$ enhanced near the coastline to $15' \times 15'$, is not adequate for properly capturing the variation in the resource throughout a region of interest.

In this work, an aid-decision tool, *i*WEDGE (Intra-annual Wave Energy Diagram GEnerator), is developed and implemented to the Death Coast, N Spain (Fig. 1), by characterizing the wave resource following a comprehensive procedure. As a result, a high-resolution dataset of the intra-annual wave energy resource is made available allowing the generation of monthly characterization matrices at any location within this coastal region and, therefore, the computation of the monthly power performance of any WEC at any location of interest. The structure of this article is as follows. In Section 2, the deep water wave energy resource is assessed in front of the Death Coast based on a large wave buoy dataset, and the energy bins providing the bulk of wave energy are selected. In Section 3, the relevant deep water information is transferred to the coast and the resulting data stored with a structure allowing its easy reading and manipulation. Next, in Section 4, the tool developed is used to produce the monthly characterization matrices at a location where a wave farm has been recently proposed. Finally, in Section 5, the most relevant conclusions are drawn, confirming the interest of the present intra-annual aid-decision tool for wave energy exploitation within a coastal region.

2. Deep water energy bin characterization

The deep water energy bins in front of the Death Coast can be accurately characterized by analysing the dataset recorded by a buoy located approximately at the middle point of the deep water boundary (Fig. 1). The buoy has been in operation since 1998 providing hourly records of the relevant parameters characterizing the wave energy resource. In particular, it provides information of the different spectral moments m_n (more specifically of the minus first and zero moments) and therefore allows the accurate computation of the spectral wave height, H_{m0}, and energy period, T_e, of each hourly sea state [21]. In addition, information regarding mean wave direction, θ_m is also available.

This large dataset is analyzed and used to compute 3D monthly matrices composed of trivariate energy bins of H_{m0}, T_e, θ_m. The selected size of the energy bins is set to 0.5 m of H_{m0}, 0.5 s of T_e and 22.5° of θ_m. For this purpose, each hourly sea state is assigned to the corresponding energy bin and its probability of occurrence, O_b, within each month determined.

The wave power of each bin is then computed according to

$$J = \frac{\rho g}{32} H_{m0}^2 \left(1 + \frac{2kh}{\sinh(2kh)}\right)\left(\frac{gT_e}{2\pi}\tanh(kh)\right) \quad (1)$$

where ρ is the density of seawater, g the acceleration of gravity, k the wave number and h the water depth at the buoy location. In deep water assumption Eq. (1) simplifies to [22]:

$$J = \frac{\rho g^2}{64\pi} T_e H_{m0}^2 \quad (2)$$

Finally, the energy provided by each bin, E_b, is obtained according to its occurrence as:

$$E_b = JO_b \quad (3)$$

In Fig. 2, the omnidirectional representation of the 3D monthly matrices (the direction is omitted for clarity purposes) covering 95% of the total available resource is shown for the months of January and July. The magnitude and distribution of the available resource amongst the different energy bins are very different.

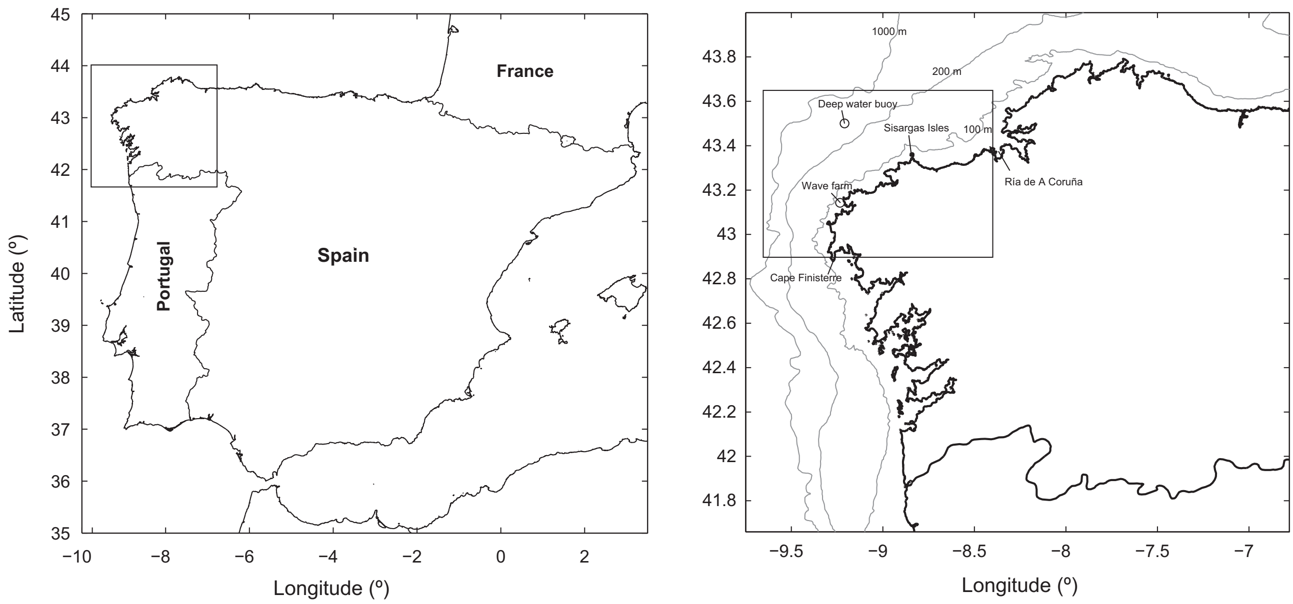

Fig. 1. General view of the Iberian Peninsula (left) and detailed of the NW coast (right) within which the Death Coast is located (square).

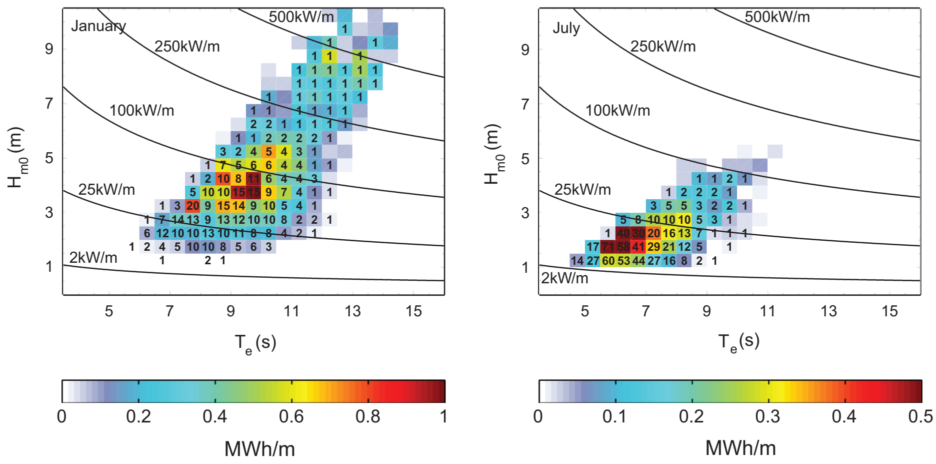

Fig. 2. January and July characterization matrices at the deep water buoy location.

Obviously, these intra-annual deep water variations will be reflected in significant variations in the resource within the region.

The next step is to transfer the trivariate energy bins thus obtained to the coastal region of interest using high-resolution numerical modelling. However, taking into account the resolution of the energy bins considered, the number of bins contributing to the total energy available is very large, and therefore propagating all of them would require a great computational effort. Instead, the most energetic bins, providing the 95% of the total energy, are considered. The remaining 5% is composed of a large number of sea states either corresponding to very low wave heights (low energy due to their low wave power) or to extreme conditions (low energy due to their low occurrence). In practice, the selection of the bins providing 95% of the available energy allows to reduce the computational effort while considering almost the entire exploitable resource.

3. Coastal resource characterization and data storage: *i*WEDGE

WECs typically operate in water depths below 120 m, corresponding to intermediate or even shallow water for many wave periods. At the boundary between deep and intermediate water, i.e., when the base of the wave "touches" the seabed, a number of changes occur, the most obvious being the change in height due to shoaling [23]. In addition, when waves propagate at an angle to the bottom contours, wave refraction occurs: the direction of wave propagation changes to become more perpendicular to the bathymetric contours, and thus wave fronts align themselves gradually with the contours. This process results in wave energy concentration in areas where the depth contours are convex (i.e., headlands) and dispersion in areas where depth contours are concave (i.e., bays) [24]. These changes may occur within short distances (hundreds of meters or even less) are therefore their analysis should be conducted through high-resolution numerical modelling.

For this purpose, the energy bins providing most of the deep water energy (95% of the total resource) are propagated to the Death Coast by implementing a high-resolution spectral numerical model capable of capturing the bathymetric configuration of the area [25]. In this work, the spectral numerical model SWAN (Simulation WAves Nearshore) [26] is used to compute the evolution of the wave spectrum. It solves the action balance equation [27]:

$$\frac{\partial}{\partial t}N + \nabla\cdot(\vec{C}N) + \frac{\partial}{\partial\theta}(C_\theta N) + \frac{\partial}{\partial\sigma}(C_\sigma N) = \frac{S}{\sigma} \tag{4}$$

where N is the wave action density, t is time, C is the propagation velocity in the geographical space, C_θ and C_σ represent the propagation velocities in the θ- and σ-space, respectively, θ and σ are the wave direction and relative frequency, respectively, and finally, S represents the sources or sinks of wave energy.

The numerical grid implemented covers the entire region of interest and extends over the continental shelf so its outer (ocean) boundary is well in deep water for all the wave periods. Regarding the lateral boundaries, they are at sufficient distance as to prevent any numerical disturbances generated at the boundaries from reaching the area of interest. The resolution of the grid allows to properly capture the bathymetric configuration of the region in the area where WECs are expected to operate (Fig. 3). This is expected to be the coastal area with water depths below 120 m excluding certain zones of great environmental value such as the rias, drowned river valleys characteristic of this region [28,29].

The energy bins selected are then propagated as defined by the spectral parameters providing the average energy instead of those corresponding to the middle point of the energy bin [25], and assuming a JONSWAP (Joint North Sea Wave Project) spectrum:

$$S = \beta H_{1/3}^2 f_p^4 f^{-5}\exp\left[-1.25(f_p f^{-1})^4\right]\gamma^{\exp\left[-(f_p^{-1}f-1)^2/2\zeta^2\right]} \tag{5}$$

where S is the spectral density, $H_{1/3}$ the significant wave height, f_p the peak wave frequency, γ the peak enhancement factor, β a parameter dependent on γ, and ζ the width of the spectral peak region (e.g., [30]).

After running the model, the relevant spectral parameters at each grid node are stored for each energy bin propagated. The wave power is calculated according to [31]:

$$J = \rho g\int_0^{2\pi}\int_0^{\infty} S(f,\theta)C_g(f,h)\,df\,d\theta \tag{6}$$

where C_g is the group celerity, and the energy associated with each wave field is obtained from Eq. (3). The resulting information comprises a dataset providing all the wave resource characterization required for power performance computations of any WEC at any coastal location throughout the Death Coast. It is composed of spectral data of trivariate energy bins of H_{m0}, T_e, θ_m for which the wave power, the monthly probability of occurrence and the total energy are available at any site within the Death Coast (at each grid node of the high-resolution numerical grid). It covers 95% of the total wave energy resource, with a resolution of the spectral parameters of 0.5 m of H_{m0}, 0.5 s of T_e and 22.5° of θ_m. This information is stored in such a way that it can be used to automatically reconstruct the

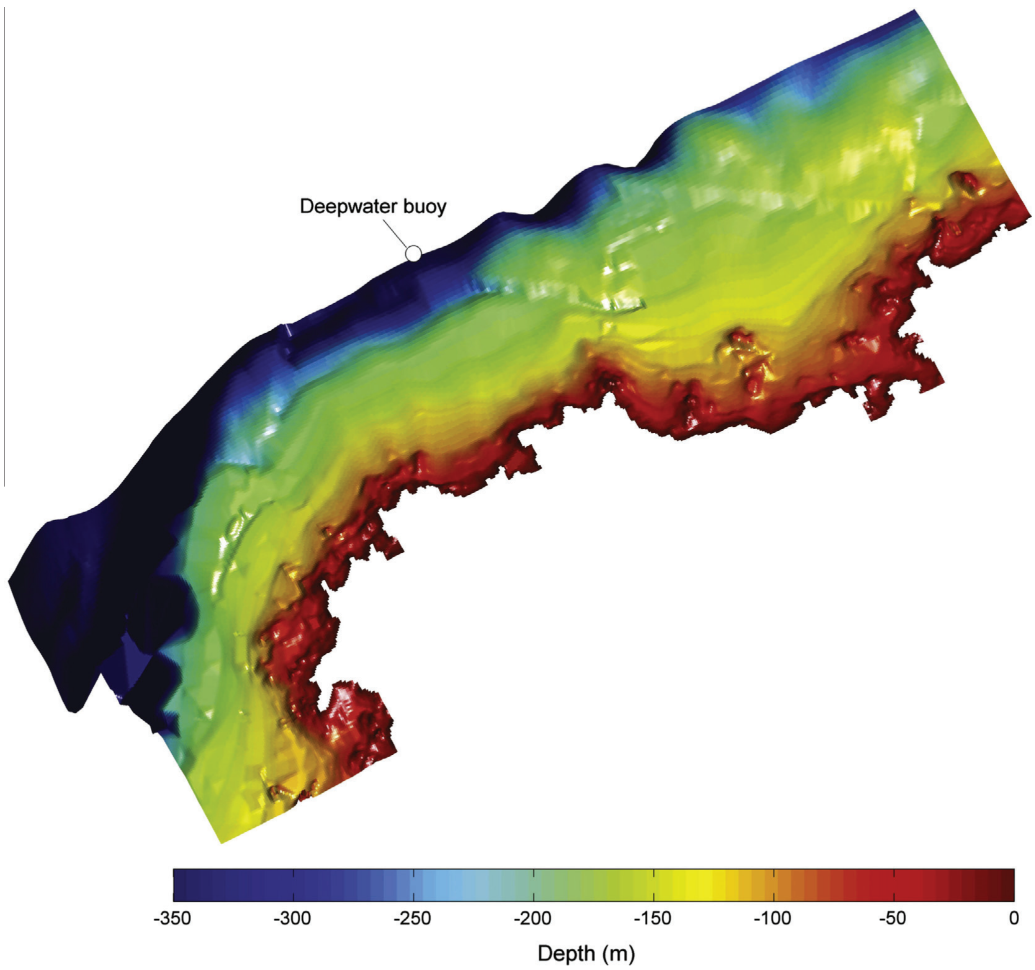

Fig. 3. View of the 3D bathymetry interpolated to the numerical grid.

monthly characterization matrices (or energy diagrams) at any coastal site.

On the other hand, the performance of a WEC is given by its power matrix (Fig. 4) which describes the power output or efficiency as a function of the spectral wave height and energy period and, where appropriate, wave direction – at present there is not information available about how direction affects the performance of WECs. This power matrix, which can be obtained through a wide

H_{m0} [m] \ T_e [s]	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0
0.5	99	109	119	129	139	149	159	169	179	189	198	208	218	228
1	397	437	476	516	556	595	635	675	715	754	794	833	873	913
1.5	893	982	1078	1061	1250	1340	1429	1518	1608	1697	1786	1875	1965	2054
2	1588	1746	1905	2064	2223	2381	2540	2699	2858	3016	3175	3334	3493	3651
2.5	2481	2729	2977	3225	3473	3721	3969	4217	4465	4713	4961	5209	5457	5705
3	3572	3929	4287	4644	5001	5358	5715	6073	6430	6787	7144	7501	7859	8216
3.5	4862	5348	5834	6321	6807	7203	7779	8265	8751	9238	9724	10210	10695	11183
4	6350	6985	7620	8256	8891	9826	10161	10796	11431	12066	12701	13336	13971	14606
4.5	8037	8841	9645	10448	11252	12056	12860	13663	14467	15271	17074	16878	17682	18486
5	9923	10915	11907	12899	13892	14884	15876	16868	17860	18853	19845	20000	20000	20000
5.5	12006	13207	14407	15608	16809	18009	19210	20000	20000	20000	20000	20000	20000	20000
6	14288	15717	17146	18575	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000
6.5	16769	18446	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000
7	19448	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000
7.5	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000
8	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000

Fig. 4. Power matrix (in kW) of SSG technology.

range of techniques such as full scale, tank or wave flume tests, as well as mathematical methods [32], is typically provided by the device developer. Combining the power matrix of the WEC of interest with the monthly characterization matrices generated at a selected location, the monthly energy output is computed, as well as other power performance parameters such as the capacity factor or the equivalent hours. Given that the maximum resolution currently available for the power matrix of WECs is 0.5 of H_{m0} and 0.5 s of T_e (the same as the resolution of the dataset generated), the power performance of any WEC could be accurately computed at any location within this coastal region by using the information herein made available. In short, this information allows the automatic computation of monthly characterization matrices, and therefore the monthly performance of any WEC, constituting a new aid-decision tool (*i*WEDGE) for the exploitation of the wave resource throughout this coastal region.

4. *i*WEDGE application

The tool is applied so as to characterize the intra-annual wave energy resource with a view to power performance computations at a location (Fig. 1) recently proposed for the installation of a wave farm [31]. To that end, the closest grid node is identified and the monthly characterization matrices are generated with the maximum available resolution (0.5 m of H_{m0}, 0.5 s of T_e). Figs. 5 and 6 show the resulting monthly characterization matrices in winter (October to March) and summer (April to September), respectively. Omnidirectional matrices are plotted for clarity. However, the tool developed can be used to generate directional matrices, should the wave direction be relevant to the performance of the WEC in question.

Overall, it can be observed that the energy bins with the largest energy contribution (the redder hues) are neither those with the

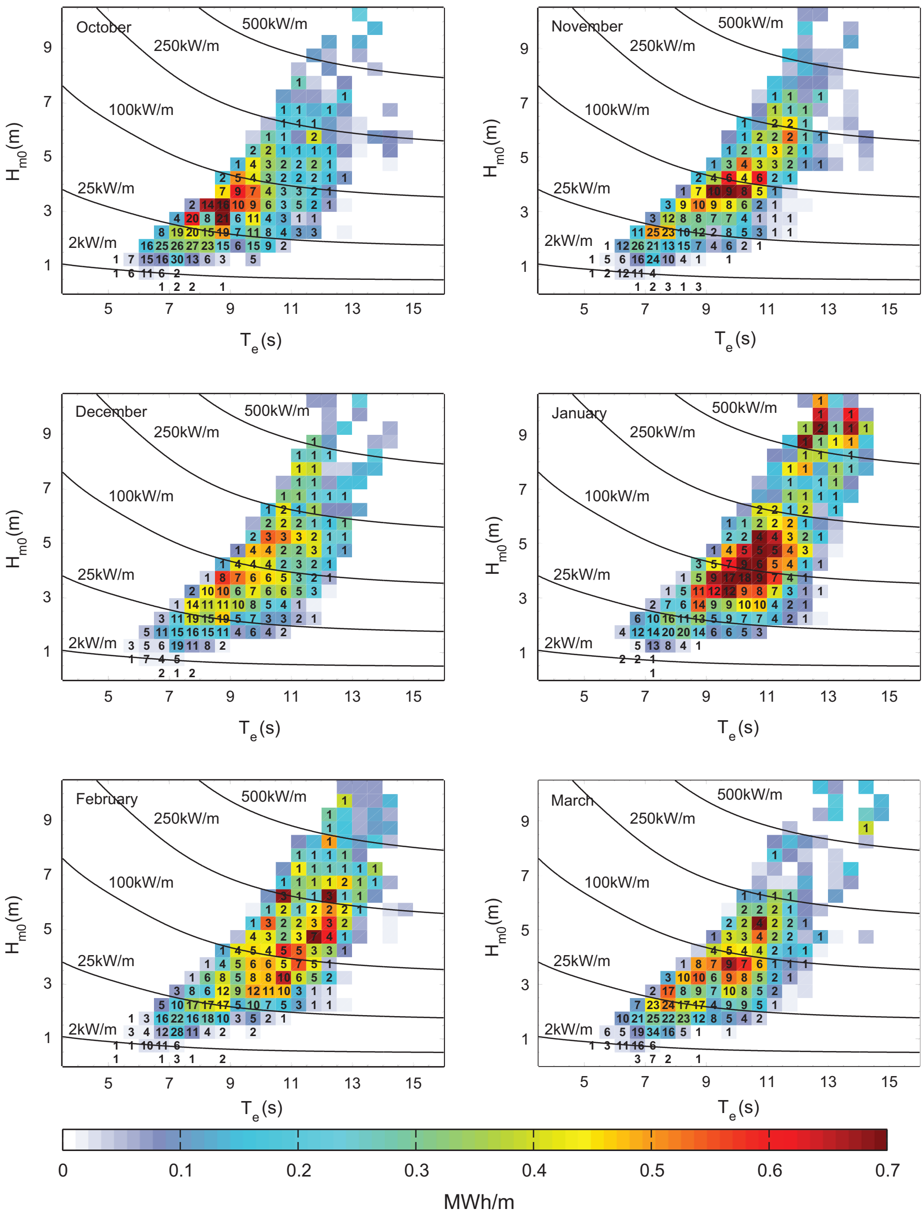

Fig. 5. Monthly characterization matrices of winter season (October–March).

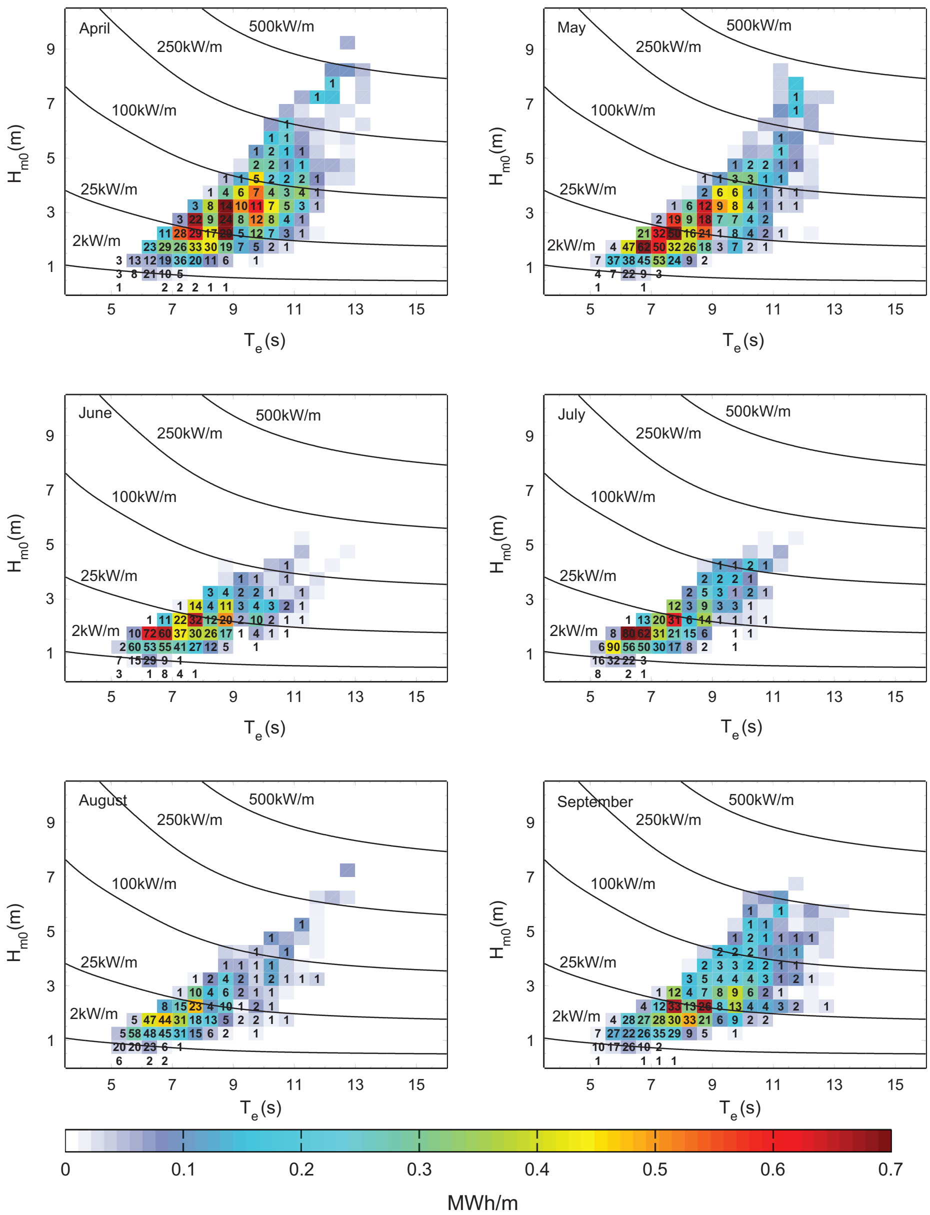

Fig. 6. Monthly characterization matrices of summer season (April–September).

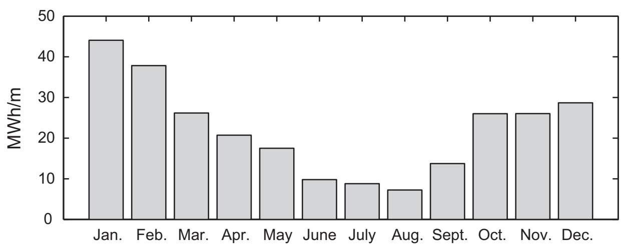

Fig. 7. Monthly distribution of the available energy.

largest wave height and period nor those with the lowest wave height or period. In the first case, the high power is offset by the low occurrence, and in the second, the high occurrence is offset by the low power. The shape of the colored area within the matrices with its apex tilted toward the right-hand side indicates the correlation between wave height and period.

With respect to the seasonal variations, it is apparent that there exist large differences between the magnitude and distribution of the energy resource between winter and summer. About 71% of the resource at this location corresponds to winter and 28% to summer. During the winter season (Fig. 5) the bulk of the energy is provided by waves with significant wave heights between 3 m and 5 m and energy periods between 8 s and 12 s. These large periods reveal the oceanic origin of the waves in the area, generated over the long Atlantic fetch. On the other hand, in summer (Fig. 6) the overall available energy is significantly lower; the bulk of energy is concentrated in wave heights from 1.5 m to 3.5 m and energy periods from 6 s to 9 s. Furthermore, a large difference between both seasons in the number of energy bins contributing to the total available resource is apparent. This derives from the fact that storms occur mostly in winter, which results in some energy bins with large wave height and period providing significant amounts of energy (shown in dark red[1] in Fig. 5).

Beyond this pronounced seasonality, large monthly differences are also present. As the winter season moves on, the reddish hues progressively move toward larger heights and periods, reaching their maximum values in January. Then, they begin to shift gradually toward lower wave heights and amplitudes (Fig. 5). This tendency is maintained until June, when this progressive displacement turns into a sudden and much more profound monthly variability (Fig. 6). Then, from June to August stability in the available resource prevails, after which the energy bins begin to shift again toward larger values of wave heights and periods, i.e., up to the values characteristic of the winter season.

This can be observed more clearly in Fig. 7, in which the total energy available in each month is shown. In effect, during the winter season, the month with the largest available resource is January, with 44.1 MW h/m, followed by February with 37.8 MW h/m; meanwhile, during October and November the available resource is about 26 MW h/m, almost 41% lower than in the case of January. In this line, differences of similar magnitude are present during the summer season. In this case, the month with the largest resource is April with 20.7 MW h/m, closely followed by May with 17.5 MW/h. On the other hand, the months with the lowest resource are June, July and August, with less than 10 MW h/m. Finally, with 13.7 MW/h September can be considered as a transitional month between summer and winter.

As a result of this pronounced monthly variability in both the magnitude and distribution of the available resource, a WEC operating at this location will experience significant fluctuations in its energy output, as well as in other performance parameters such as the capacity factor or equivalent hours, the analysis of which is fundamental for proper decision making in any wave energy project.

5. Conclusions

The selection of the most adequate WEC for a site of interest as well as the definition of its most appropriate configuration is of key importance for the exploitation of the wave energy resource. For this purpose, an accurate analysis of its power performance should be conducted, for which it is necessary to characterize the energy resource at the location of interest in a specific way: a characterization matrix or energy diagram showing the energy distribution and occurrence of the different combinations of the relevant spectral parameters (or energy bins) with the adequate level of resolution.

Furthermore, the wave resource is typically subjected to an important intra-annual variability which leads to significant intra-annual fluctuations in the WECs' performance. For this reason, assessing the energy output of a wave farm on the basis of average annual figures would likely result in ill-informed decision making, and may pose a threat to the economic viability of the farm. Therefore, it is necessary to characterize the resource in the form of intra-annual matrices that capture the variability of the resource.

In this work, an aid-decision tool for wave energy exploitation, *i*WEDGE (intra-annual Wave Energy Diagram GEnerator), is developed and implemented to a coastal region with a substantial wave resource, the Death Coast, so as to provide the information required for reconstructing the wave resource in the form of monthly energy matrices with the required level of resolution. For this purpose, a procedure for characterizing the wave energy resource is implemented, which includes the consideration of a large dataset of deep water data, as well as the implementation of a high-resolution numerical model.

The resulting information is stored in such a way that allows its easy access and manipulation. It consists of data of wave power and monthly occurrence (and therefore energy available) for the different combinations of significant wave height, energy period and mean wave direction (or trivariate energy bins) covering 95% of the total energy resource available. The resolution of the energy bins corresponds to the maximum resolution of the bins of the WECs' performance provided by the device's developers (0.5 m of significant wave height, 0.5 s of energy period). With respect to wave direction, a resolution of 22.5° is provided. This information is made available with a high spatial resolution (at each node of the high resolution numerical grid), thereby allowing the computation of monthly matrices at any costal location throughout the Death Coast.

Finally, the tool herein developed is applied to generate the monthly characterization matrices at a coastal location of special interest within the Death Coast, where a wave farm has recently been proposed. The results show that there exists a significant intra-annual variability in the energy resource which goes far beyond seasonal differences. Indeed, except in the months with lowest resource (June–August) significant monthly differences are observed (up to 40% within each season).

In sum, in this work an aid-decision tool for the exploitation of the wave energy resource is developed. This tool is implemented to the Death Coast, allowing the automatic generation of high-resolution monthly characterization matrices at any location within this coastal region, the information required for accurate power performance computations of WECs. The results obtained highlight the importance of characterizing the resource on the basis of monthly figures so as to properly analyze the power performance of a WEC at a given location. Although at present this tool only contains information for the Death Coast, the same procedure could be implemented in any other region where large deep water dataset is available so as to provide the same aid-decision tool. In future work, this tool will be extended so as to cover the Atlantic Region of the Spanish Coast.

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[1] For interpretation of color in Fig. 5, the reader is referred to the web version of this article.

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A holistic methodology *cum* database for wave energy exploitation: Implementation on the Galician coast (NW Spain)

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The intra-annual variability in the performance of wave energy converters: A comparative study in N Galicia (Spain)

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The intra-annual variability in the performance of wave energy converters: A comparative study in N Galicia (Spain)

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ABSTRACT

This paper presents the analysis of the intra-annual power performance of different WECs (wave energy converters) at two locations of interest in the northern coastal region of Galicia (NW Spain). With this aim, the wave resource at the locations of interest is characterised by considering a procedure whose implementation on a coastal region produces the required wave spectral information for reconstructing the coastal resource in terms of monthly characterisation matrices with the adequate resolution for conducting accurate performance computations of WECs. Next, the monthly performance of different WECs at these locations is estimated through the combination of the characterisation matrices obtained and the efficiency of the technologies analysed. The results show that the analysis of the intra-annual performance of different technologies at different locations is a key aspect so as to define the most appropriate WEC-site combination for harnessing the wave energy resource in a coastal region. Finally, the information produced by implementing the methodology considered in this work allows the reconstruction of the wave resource at any coastal site (not only at the selected locations), in the form of monthly high resolution characterisation matrices, and thus, the monthly performance of any WEC-site combination can be computed.

1. Introduction

Wave energy has shown to be one of the most promising energy resources (e.g., Refs. [1–4]). Alike other renewable energies, the installation of a wave farm in an appropriate location is of paramount importance stemming from the large spatial variations in the resource. However, in contrast with other renewables, there is not a single established technology providing the largest energy production and performance throughout a coastal region. Instead, a gamut of WECs (wave energy converters) is currently available whose efficiency is highly dependent on the wave conditions [5].

WECs can be classified according to their i) distance to the coast, ii) shape and direction and iii) principle of operation [6]. Following iii), three different types of technologies can be distinguished: overtopping devices [7–9], oscillating water columns [10,11], and wave activated bodies [12]. As stated, their efficiency depends on the characteristics of the resource at the site where they operate, and more specifically on the wave height and period conditions of the different sea states, as it is expressed by their power matrices. Therefore, the selection of the most appropriate site and technology for wave farm operation in a region should be based on a thorough analysis of the performance of different WEC-site combinations, for which an accurate resource characterisation at each location of interest should be conducted [13].

On the other hand, numerous studies [14–17] have shown that the wave resource throughout the most powerful coastal regions exhibits a significant intra-annual variability. This is the case of the Iberian Peninsula, and in particular of the Atlantic coast of Spain (e.g., Refs. [18,19]), and Portugal (e.g., Refs. [20,21]) whose resource has been widely studied. Thus, it emerges that an intra-annual analysis of WECs' performance is required prior to the installation of a wave farm. Furthermore, these assessments showed that some areas, as it is the case of the northern coast of Galicia (NW Spain) (Fig. 1), boast a large resource, providing valuable information about the locations with the greatest potential [22] for wave energy exploitation.

In this work, the importance of analysing the intra-annual performance provided by different WECs at different locations is

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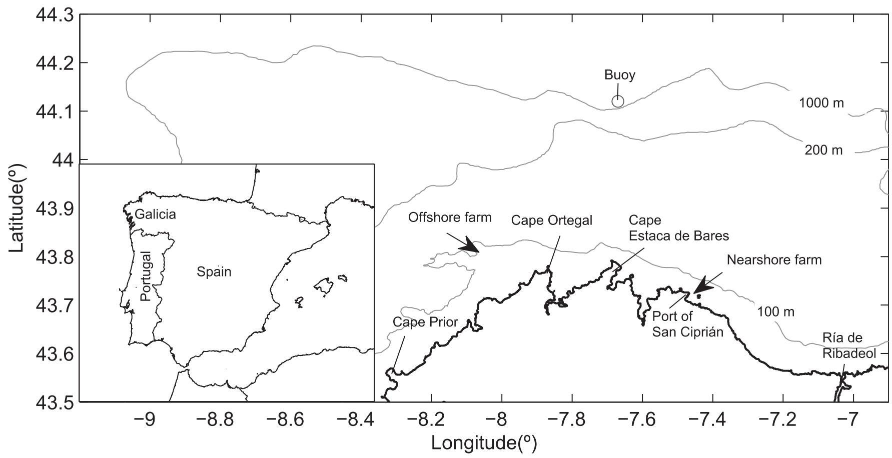

Fig. 1. Northern coastal region of Galicia (left) in NW Spain (right). The arrows indicate the sites proposed for wave energy exploitation and the circle the deepwater buoy location.

analysed by means of a case study in the northern coast of Galicia. For this purpose, the monthly performance of different WECs is computed at two coastal locations (offshore and nearshore) where different wave farms have been previously proposed [22,23] (Fig. 1). With this aim, the nearshore resource is thoroughly assessed by implementing a comprehensive procedure allowing the generation of the required information for conducting performance computations of WECs. This assessment is performed by considering the methodology presented in Ref. [24] in which is applied to the Death Coast (NW Spain) and used for the development of the tool called WEDGE (Wave Energy Diagram GEnerator). The implementation of this procedure on a coastal region enables the characterisation of the available resource at any coastal site in the form of an annual high resolution characterisation matrix, or in other words, the required information for accurate annual power performance computations —the energy production of a WEC at a coastal site is the result of combining the characterisation matrix of the resource at the coastal location and the power matrix of the selected WEC. In this study, this methodology is implemented on the northern coast of Galicia and extended so as to consider the monthly variations of the resource, thereby allowing the computation of the monthly performance of any WEC-site combination.

The structure of the paper is as follows. First, in Section 2, the procedure considered for the deepwater assessment of the resource is presented and implemented to the region of interest. In Section 3, the intra-annual characterisation matrices at the selected locations are reconstructed. In Section 4, the performance of different WECs is computed and the results thoroughly analysed. Finally, in Section 5 the main conclusions of this work are drawn.

2. Deepwater resource analysis

2.1. Site selection

The propagation of waves from deepwater to the shore results in an overall reduction of the available energy resource [25]. However, as a result of the refraction process [26] wave energy concentrates at specific sites, which are of highest interest for wave energy exploitation, and thus should be properly identified. In this vein, previous assessments analysed the wave patterns along the coast of N Galicia, and more specifically in the area around Cape Estaca de Bares [22] (Fig. 1). It was shown that this area boasts a very substantial resource, with average wave power up to 40 kWm^{-1}, and therefore it emerges as a promising area for wave energy exploitation. In particular, in Ref. [22] a numerical model of the area was implemented and various conditions analysed, including average, growing (approach of a storm), extreme and decaying (recession of a storm) wave energy conditions. On the basis of the numerical results, different coastal points were identified as sites where significant energy concentration exists, stemming from the complex bathymetry configuration. These results, as well as the consideration of other socioeconomic factors, led to the definition of various sites of great interest for the installation of a wave farm [22,23]. Two of these sites, one nearshore (at 20 m depth) (located close to the Port of San Ciprián) and another offshore (at 70 m depth) (Fig. 1) are retained in this work to analyse the intra-annual performance of different WECs.

These locations were simply defined on the basis of the power available under a few wave conditions. In this vein, it is important to keep in mind that the energy production, and therefore the performance, of a given WEC-site combination is the result of combining the power matrix of the selected WEC with the resource characterisation matrix with the adequate level of resolution at the coastal location of interest (containing the information of the total energy available and occurrence for the different wave height and period combinations), which in addition should cover a time period enabling to capture the temporal variability of the resource [24]. Therefore, despite the great interest of these previous assessments, they do not provide sufficient information so as to conduct intra-annual performance computations at these coastal sites.

2.2. Wave data

The wave data required for assessing the resource in terms of high resolution intra-annual characterisation matrices is currently only available at sites where a buoy has been operating during several years or where hindcast data is available [27,28], which in turn are not normally the locations of interest for the exploitation of the wave energy resource. In this work, in order to obtain an accurate resource assessment in terms of monthly characterisation matrices at the selected locations, the resource in deepwater is analysed and propagated to the sites of interest following a specific procedure [24]. For this purpose, the spectral records of a buoy located at a site of coordinates (7.67° W, 44.12° N) (Fig. 1) and moored in a water depth of 1800 m are analysed. The dataset comprises almost 100,000 hourly sea states (1996–2014), with information of different spectral parameters from which the wave height, H_{m0}, energy period, T_e, and mean wave direction, θ_m, are computed [29,30].

The next step consists in propagating the wave conditions of interest towards the selected locations. Nevertheless, it is important to bear in mind that not all the sea state records can be propagated since the computational cost would be enormous. In practice, the assessments conducted by using the common procedure merely consider some conditions of interest (those referred to either average and/or high energetic conditions) for being propagated (at it is the case of the previous studies in the region). Thus, the information made available following this common procedure does not allow the reconstruction of the resource in the form of a characterisation matrix at a specific location of interest. With this in view, in this work, instead of analysing specific sea states, the most representative wave conditions covering 95% of the total energy resource are selected and retained for being propagated through numerical modelling. This level of energy has shown to represent virtually 100% of the exploitable resource [24].

2.3. Selection of wave conditions

The most representative deepwater wave conditions to be propagated are selected by using the following procedure [24]. First, the conditions are defined as trivariate *energy bins* [31], or in other words, intervals of the three relevant spectral parameters, H_{m0}, T_e, θ_m with an specific size. The key aspect is to select the adequate size of the intervals. Based on previous studies [32], a resolution of 0.5 of H_{m0}, 0.5 s of T_e (the maximum resolution of WECs' power matrices currently available) and 22.5° is selected. Then, each of the approx. 100,000 sea states recorded is assigned to its corresponding bin within each month [e.g. H_{m0} = 4–4.5 m, T_e = 11–12 s, θ_m = 303.75–326.25°] and the resulting energy calculated as:

$$E_b = J_b O_b \tag{1}$$

where E_b is the energy provided by each bin, O_b, its occurrence and J_b its wave power calculated following linear theory (e.g., Ref. [33]).

Finally, the bins with the largest energy which provide 95% of the total available energy are retained for numerical model propagation. This is achieved just by considering 693 bins, rather than almost 100,000 sea states that would be required for covering 100% of the resource.

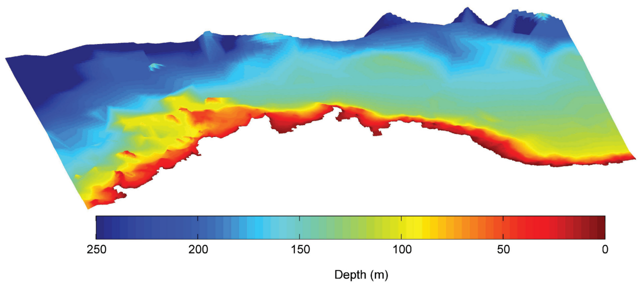

Fig. 3. Three-dimensional representation of the bathymetry configuration in the region.

3. Coastal resource characterisation

3.1. Coastal modelling

The spectral numerical model SWAN (Simulation WAves Nearshore) [34–36] is implemented to the coastal region of interest and used to propagate the selected 693 wave conditions.

The key aspect lies in the selection of the adequate spatial resolution of the numerical grid allowing to properly solve the different transformation processes experimented by waves in their propagation to the shore. The region herein analysed presents an irregular and complex bathymetry which has been shown to provoke strong variations in the wave conditions in short distances [22]. On this basis, a grid with a resolution of 200 m is implemented (69,969 grid points) (Fig. 2), which is interpolated to a total of 114,751 depth datapoints obtained by digitizing the nautical charts of the Spanish Hydrographic Institute available in the area. In Fig. 3, the numerical grid as interpolated to the bathymetry is shown.

3.2. Wave resource reconstruction

Once the different wave cases are propagated, the spectral information made available at each grid node, and in particular at each location of interest, consists of 693 spectral wave conditions (the number of wave cases considered) representing 95% of the

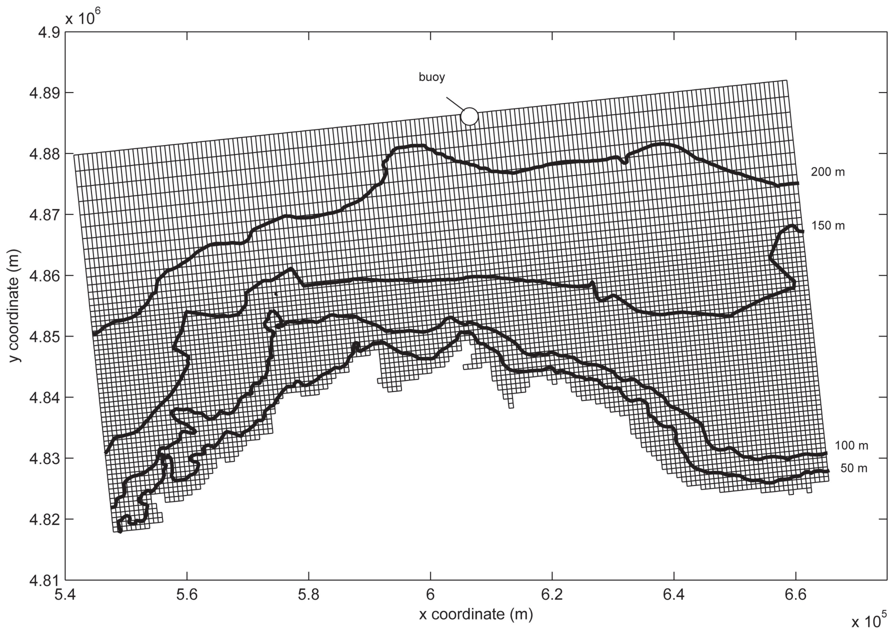

Fig. 2. High resolution numerical grid (for clarity only one in three line coordinates are shown).

total energy. More specifically, the spectral parameters of interest computed are H_{m0}, T_e, θ_m allowing the characterisation of the resource with a resolution of 0.5 m of H_{m0}, 0.5 s of T_e, and 22.5° of θ_m (the resolution used to propagate the energy bins to the coast). Furthermore, the monthly occurrence of each wave case propagated is also known, given that it was previously computed (Section 2.3) and is conserved through wave propagation. Thus, the energy provided by each energy bin at the grid nodes corresponding to the locations of interest can be computed using Eq. (1), following the same procedure as explained in Section 2.3.

Figs. 4 and 5 show the omnidirectional matrices obtained at the nearshore and offshore locations, respectively, by using the resulting data (for simplicity, only one in two months is plotted). It can be observed that a significant intra-annual variability is present

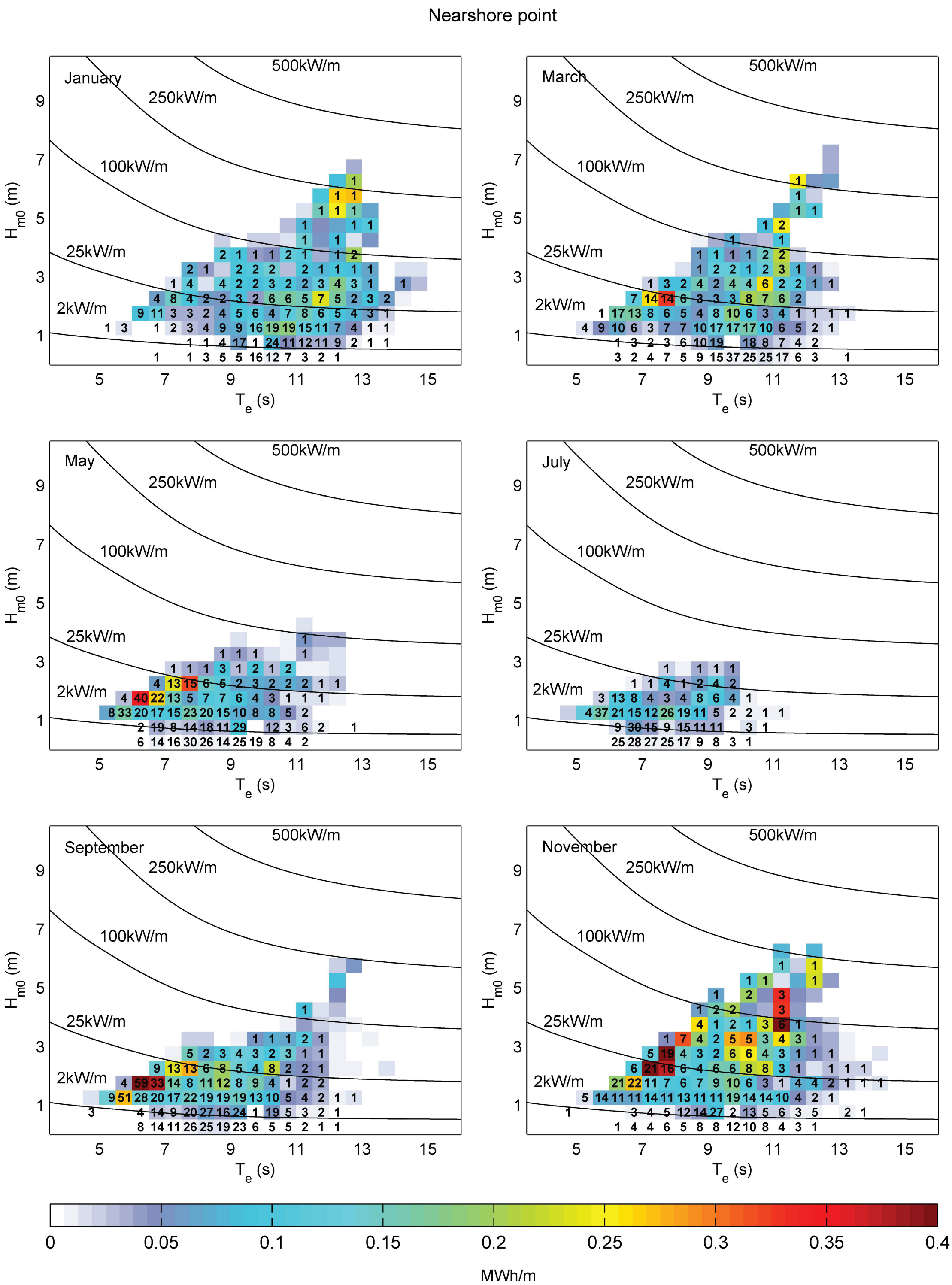

Fig. 4. Omnidirectional monthly characterisation matrices of the resource at the nearshore location (resolution 0.5 m × 0.5 s) (For simplicity, only one in two months are shown).

at both locations, going far beyond mere seasonal variations. This variability consists not only in large variations in the magnitude of the available resource, but also in strong variations in the energy distribution amongst bins. Furthermore, the differences in the wave energy resource between both locations are also apparent. At the offshore point, a very strong correlation between wave height and period is observed, which results in a characteristic shape of the energy distribution (coloured plot) but occupying a different position depending on the period considered. By contrast, at the nearshore site this distribution is less marked, which is explained by its location near the coast and its reduced depth, thereby causing waves to experience sharper transformation processes than in the

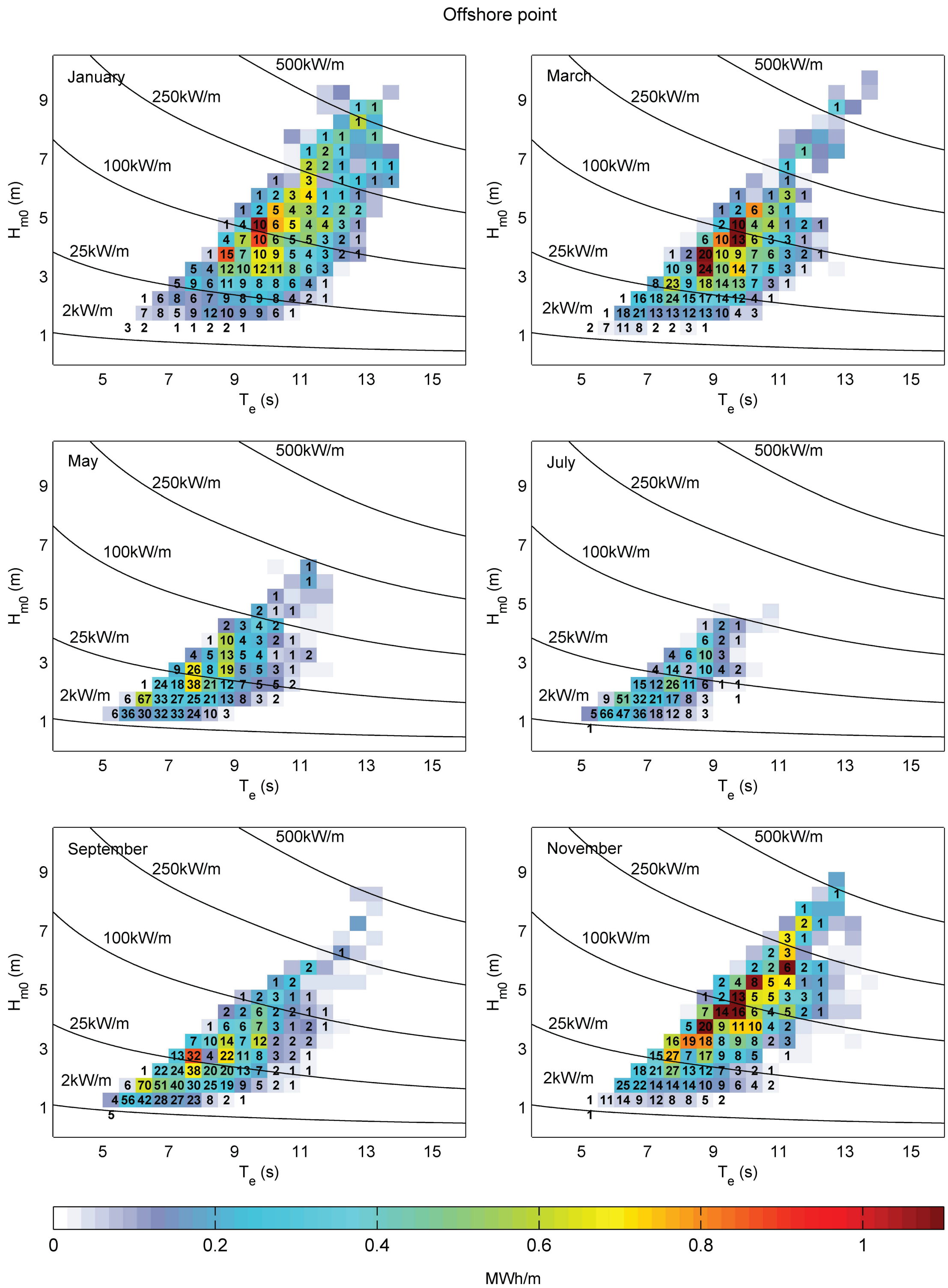

Fig. 5. Omnidirectional monthly characterisation matrices of the resource at the offshore location (resolution 0.5 m × 0.5 s) (For simplicity, only one in two months are shown).

case of the offshore location. These differences in the distribution of the resource will led to large differences in the performance of the WECs that need to be analysed prior to installing a wave farm.

4. Monthly power performance computations

In this section, the monthly power performance provided by different technologies at the two proposed locations is assessed. At the nearshore point the technologies analysed are Pelamis, Oyster and B-HBA whereas at the offshore point the technologies considered are Pelamis, AWS (Archimedes Wave Swing) and Aqua Buoy [37,38]. The characteristics of the technologies considered are summarized in Table 1.

As stated, the performance of a selected WEC is the result of combining the data contained within the characterisation matrices generated at the location of interest (Section 3) with the WEC's efficiency data provided by its device developer. This data consists in a power matrix providing the efficiency or power output of the WEC for the different intervals of wave height and period combinations (energy bins) (Fig. 6). Therefore, it is enough to combine the characterisation matrices with the WECs' power matrices for computing the total energy output and the remaining power performance parameters of interest (which naturally would be referred to the period covered by the characterisation matrix).

The monthly energy output E_o [Mwh] is computed as:

$$E_o = \sum P_b O_b \tag{2}$$

where P_b is the power output provided by the WEC considered for each energy bin as expressed in its power matrix, and O_b the occurrence of the corresponding bin at the locations of interest.

Furthermore, given that the energy delivered by the different WECs analysed could significantly differ depending on the total power installed, in addition to E_o, the capacity factor, C_f, is also computed. It compares the energy production of the WEC during a given period with the energy it would have produced if it had operated at full capacity or maximum power, P_m. This parameter is expressed as:

$$C_f = \frac{E_o}{P_m n} \tag{3}$$

where n is the total number of hours of the period considered.

In Figs. 7 and 8 E_o and C_f are plotted for the different technologies considered in the nearshore and offshore locations, respectively. Overall, large differences in these parameters exist throughout the year, both between the different technologies and locations analysed.

In the case of the nearshore point, the largest E_o is provided by B-HBA, doubling the values obtained with Oyster and closely followed by Pelamis with monthly average values of 114.8, 63.0 and 56.5 MWh, respectively. However, they describe a fairly similar intra-annual pattern with their differences (in relative terms) approximately maintained throughout the year (the change in these positions only occurs in November, where the E_o of Pelamis is slightly higher than Oyster). The general picture is as follows. Over the first third of the year (from January to April) a certain stability in E_o is apparent with figures similar to the monthly average values. Then, E_o begins to show a steady reduction lasting until July when it bottoms out with 58.4, 34.6 and 29.1 MWh, respectively. After summer, the energy output picks up with the last third of the year being a period of important fluctuations in E_o. The month with the greatest E_o is November with 180.9, 88.9 and 89.2 MWh, indicating 210, 157 and 207% higher than July's figures. Regarding C_f, although its variability describes the same pattern as E_o (they are related by the fixed parameter $P_m n$), the results greatly differ from those obtained for E_o. Indeed, the technology with the largest $E_{o,}$ B-HBA, now provides the lowest C_f. The monthly average values of C_f are 0.298, 0.101 and 0.058 for Oyster, Pelamis and B-HBA, respectively, again maintaining these positions throughout the year. During July C_f drops to its minimum with values of 0.160, 0.052 and 0.029, whereas in November it reaches its maximum with 0.426, 0.160 and 0.093, indicating an upturn of 166, 208 and 221%, respectively.

Regarding the offshore point, the trend in the intra-annual variability of the performance presents some similarities with respect to the nearshore location but with significant larger magnitudes. Now the greatest E_o is delivered by AWS with a monthly average value of 255.7 MWh, followed by Pelamis and Aqua Buoy with 146.6 and 50.3 MWh, respectively, and invariably maintaining these respective positions throughout the year. However, in contrast with the nearshore location, there exist important differences amongst them regarding the variability of E_o, up to the point that during the summer months (June, July and August) E_o is almost the same for AWS and Pelamis. Over the first third of the year a certain stability in E_o is again present with the exception of AWS. Then, E_o begins to progressively decrease up to June, the month with the lowest figures with 82.1, 80.0 and 23.0 MWh, respectively. Summer can be considered a season of some stability, with E_o at a consistently lower level. During the last part of the year E_o picks up steadily – in contrast with the nearshore location where important fluctuations exist – up to November when again the values reach their peak with 397.0, 204.4 and 72.9 MWh, indicating 384, 156 and 217% higher than June's figures. The values of E_o are much higher in the offshore location than in the nearshore point, which is in connection with the greater resource available offshore, as it emerges from the considerably greater E_o delivered by Pelamis offshore than nearshore. By analysing the results of C_f, further interesting information stands out. The monthly average values computed of C_f are 0.270, 0.263 and 0.143 for Aqua Buoy, Pelamis and AWS, respectively, overall significantly higher than nearshore with the exception of Oyster. This is of special interest in the case of the AWS and Pelamis technologies. AWS provides the largest E_o offshore, much higher than Oyster nearshore, but with lower C_f, which is explained by its greater maximum power. With respect to Pelamis, it provides not only a considerable higher E_o offshore than nearshore (which may result, as stated, from the larger energy available offshore), but also a greater C_f (similar to that of Aqua Buoy) resulting from it being more adapted to operate offshore than nearshore. This clearly indicates that, in addition to the available resource, the efficiency of the technology for the wave conditions at a selected location may also play a major role.

Table 1
Characteristics of the technologies considered.

Technology	Location	Resolution ($H_{m0} - T_e$) power matrix
Pelamis	Nearshore-offshore	0.5 m–0.5 s
AWS	Offshore	0.5 m–0.5 s
Oyster	Nearshore (reduced depths)	0.5 m–1 s
Aqua Buoy	offshore	0.5 m–1 s
B-HBA	Nearshore (reduced depths)	0.5 m–1 s

5. Conclusions

The exploitation of the wave energy resource in a coastal region is based on the definition of two main aspects: the most appropriate site and WEC. These two aspects are profoundly interconnected, resulting from the performance of WECs being highly dependent on the wave conditions, which in turn may largely vary

Pelamis	T_e [s]																
H_{m0} [m]	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0
0.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1	0	22	29	34	37	38	38	37	35	32	29	26	23	21	0	0	0
1.5	32	50	65	76	83	86	86	83	78	72	65	59	53	47	42	37	33
2	57	88	115	136	148	153	152	147	138	127	116	104	93	83	74	66	59
2.5	89	138	180	212	231	238	238	230	216	199	181	163	146	130	116	103	92
3	129	198	260	305	332	340	332	315	292	266	240	219	210	188	167	149	132
3.5	-	270	354	415	438	440	424	404	377	362	326	292	260	230	215	202	180
4	-	-	462	502	540	546	530	499	475	429	384	366	339	301	267	237	213
4.5	-	-	544	635	642	648	628	590	562	528	473	432	382	356	338	300	266
5	-	-	-	739	726	731	707	687	670	607	557	521	472	417	369	348	328
5.5	-	-	-	750	750	750	750	750	737	667	658	586	530	496	446	395	355
6	-	-	-	-	750	750	750	750	750	750	711	633	619	558	512	470	415
6.5	-	-	-	-	750	750	750	750	750	750	750	743	658	621	579	512	481
7	-	-	-	-	-	750	750	750	750	750	750	750	750	676	613	584	525
7.5	-	-	-	-	-	-	750	750	750	750	750	750	750	750	686	622	593
8	-	-	-	-	-	-	-	750	750	750	750	750	750	750	750	690	625

Oyster	T_e [s]								
H_{m0} [m]	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0
0.5	0	0	0	0	0	0	1	3	3
1	20	30	38	42	44	44	45	47	45
1.5	80	85	92	97	102	103	104	100	104
2	140	147	152	158	155	155	160	161	156
2.5	192	197	208	202	203	209	211	201	204
3	241	237	237	241	243	230	236	231	235
3.5	-	271	272	269	268	267	270	260	260
4	-	291	290	290	280	287	276	278	277
4.5	-	291	290	290	280	287	276	278	277
5	-	-	290	290	280	287	276	278	277
5.5	-	-	290	290	280	287	276	278	277
6	-	-	290	290	280	287	276	278	277

Fig. 6. Power matrices of Pelamis (above) (resolution 0.5 m × 0.5 s), and Oyster technologies (below) (resolution 0.5 m × 1 s) showing the efficiency (in terms of power output [kW]) for the different wave height and period combinations.

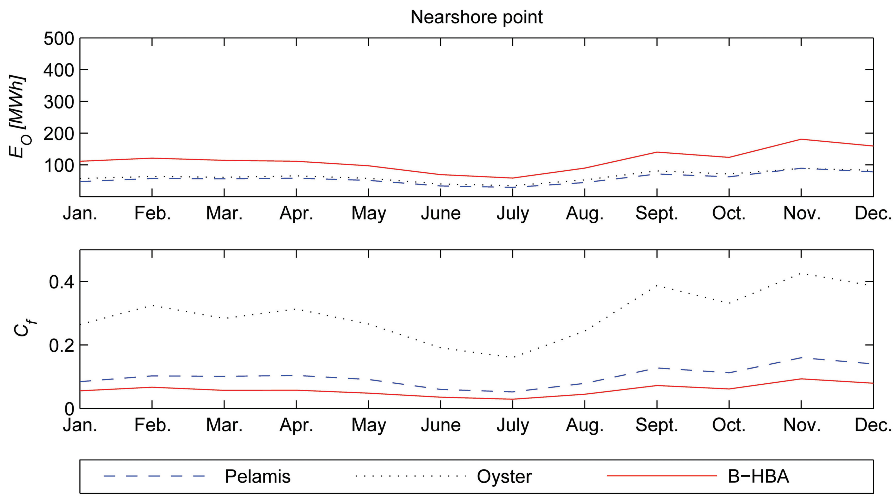

Fig. 7. Power performance at the nearshore location in terms of energy production, E_o, (above) and capacity factor, C_f, (below) for Pelamis, Oyster and B-HBA technologies.

within short distances. Previous works showed that most of the regions with significant wave energy potential present a relevant intra-annual variability of the resource, which must be accounted for when examining the operation of WECs.

In this work, the importance of conducting an analysis by considering the aforementioned factors, with a particular focus on the variability of the intra-annual performance, is illustrated through a case study in the northern coast of Galicia (NW Spain). For this purpose, the monthly performance of different WECs is computed at two locations (nearshore and offshore) previously proposed for the installation of a wave farm. With this aim, the wave resource is characterised by implementing a methodology previously used for developing the tool WEDGE, allowing the generation of annual characterisation matrices at any coastal site of

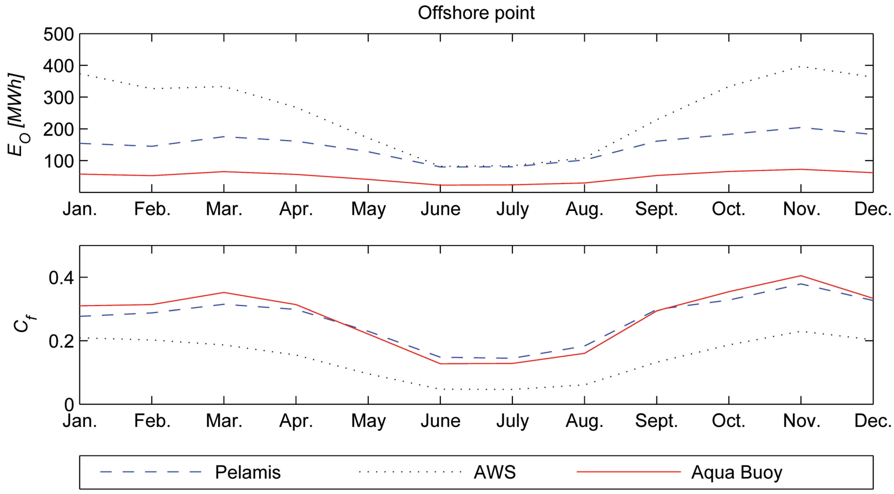

Fig. 8. Power performance at the offshore location in terms of energy production, E_o, (above) and capacity factor, C_f, (below) for Pelamis, AWS and Aqua Buoy technologies.

interest, which is modified so as to account for the intra-annual variation of the resource. A number of deepwater energy bins is selected enabling to consider 95% of the total energy, with a resolution of 0.5 m of significant wave height, 0.5 s of energy period, and 22.5° of mean wave direction. Wave conditions representative of each of these bins are then propagated from deepwater to the locations of interest by using high resolution numerical modelling. The spectral information resulting from the numerical model propagations, together with the information of the monthly probability of occurrence of each energy bin, allows the reconstruction of monthly characterisation matrices with the required level of resolution for power performance computations. In the next step, the characterisation matrices are combined with the power matrices of the different devices considered, and their performance computed in terms of energy output (E_o) and capacity factor (C_f). The technologies analysed are Pelamis, Oyster and B-HBA at the nearshore location and Pelamis, AWS and Aqua Buoy at the offshore location.

The large differences in the available resource throughout the year are reflected in significant intra-annual variations in the performance of the WECs considered. Indeed, the results indicate that there exist differences in the monthly energy output of more than 150% for all the technologies analysed, attaining 384% in the case of AWS between November and June at the offshore location. These variations in the energy output are reflected in similar variations in the capacity factor. Furthermore, there exist significant intra-annual differences between both the technologies and locations considered. In the case of the nearshore location, the largest energy output is provided by B-HBA, with an average monthly output of 114.8 MWh; however, this technology provides the lowest capacity factor with 0.058. At the offshore point, AWS is the device delivering the greatest energy output, with a monthly average output of 255.7 MWh, which again is that providing the lowest capacity factor with 0.143. Overall, the energy output at the offshore location is much higher than at the nearshore site, stemming from the greater resource available; nevertheless, the results also indicate that the efficiency of the different technologies (expressed in terms of power output in their power matrices) for the wave conditions, which may differ significantly between locations, also plays a major role in selecting the most appropriate technology. This is clearly the case of the Pelamis technology which, as a consequence of its higher efficiency for the offshore wave conditions than for the nearshore, provides a low performance at the nearshore site but the best results at the offshore location (the technology with the greatest capacity factor together with Aqua Buoy but with a larger energy output).

In sum, the results obtained highlight the importance of conducting the analysis implemented in this work so as to select the most appropriate wave farm configuration (technology and location) in a coastal region. In particular, the intra-annual performance provided by the different currently available WECs at different coastal locations of interest should be accurately computed and analysed.

Finally, it is important to note that, as a result of the methodology herein implemented, the relevant spectral parameters are computed (and stored) with a high spatial resolution throughout the whole coastal region. Therefore, although in the present work the power performance of WECs is only investigated at two specific locations, the data made available could be used to compute the intra-annual power performance parameters of any WEC at any site within this coastal region. Furthermore, this methodology could be implemented in any other coastal region in order to provide the required data for accurate intra-annual power performance computations for any WEC-site combination.

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VI

General discussion

General discussion

1. Wave resource characterization for WEC performance computations

This thesis develops a holistic methodology *cum* database for characterizing the wave energy resource so as to provide the elements for computing the performance of any WEC at any location within a coastal region of interest. The methodology comprises three main steps: (i) the selection of the energy bins providing the bulk of the energy in deep water based on wave buoy records; (ii) the propagation of the energy bins by means of spectral numerical modelling; (iii) the reconstruction of the energy bins at any site throughout the coastal region of interest.

The first step consists in the selection of the energy bins at a location within the coastal region of interest where a large dataset of deepwater sea states records are available. With this aim, the deepwater wave resource is characterized by the probability of occurrence of trivariate intervals of significant wave height, H_{m0}, energy period, T_e, and mean wave direction, θ_m, or trivariate energy bins. A key aspect for conducting an accurate wave energy characterization is the selection of the appropriate bin size. Currently WEC efficiency is provided by technology developers as a function of H_{m0} and T_e, assuming that it does not vary according to wave direction. Hence, it emerges that the energy production of a WEC at a coastal location will be the result of combining the power matrix of the technology selected with the omnidirectional resource's characterization matrix at the same level of resolution (size of energy bins) at the location of interest. Therefore, the size of the deepwater energy bins —which will be propagated so as to compute the characterization matrices throughout the coast— should have the same level of resolution of H_{m0} and T_e intervals as that of the WEC power matrix of interest. Based on the current power matrices available (Babarit *et al.*, 2012; Silva et al., 2013; The Carbon Trust, 2010), the resolution of H_{m0} and T_e intervals is set to 0.5 m and 0.5 s, respectively, which corresponds to the highest resolution currently provided by WECs' developers. With regard to θ_m, which is also required in order to transfer the wave energy from deepwater towards the coast, the resolution should properly capture the wave directionality of the resource, which in turn is highly dependent on the characteristics of the region considered.

Once the resolution of the energy bins is defined, each deepwater sea state recorded at the buoy location is assigned to the corresponding trivariate bin, the resulting wave power, J, computed, and the total energy provided by each bin, E_b, determined according to its probability of occurrence, O_b. Finally, the bins providing the bulk of the energy are selected and retained to be propagated towards the coast through numerical modelling. Although within the conventional procedure a handful of study cases are usually considered, recent studies have shown the importance of considering a high percentage of the total energy (90-95%) (Iglesias and Carballo, 2011b), resulting in a more accurate characterization of the resource and, in consequence, of power performance computations of WECs. In practice, it requires the consideration of a large number of energy bins, which means propagating a large number of wave conditions and, as a result, a greater computational effort. In this way, the selection of the energy bins should be conducted on the basis of the total energy provided by each bin, thereby allowing the consideration of a higher percentage of the total energy available for a given number of wave cases considered, i.e., more accurate results with the same computational effort.

The next step of the methodology, as stated, consists in transferring the deepwater wave resource (or deepwater energy bins) towards the coastal area of interest. For this purpose, the energy bins selected are propagated through spectral numerical modelling by considering each of them as a wave case as defined by their spectral parameters (H_{m0}, T_e, θ_m) that best represent the wave conditions within the bin —those providing the average energy—. In this context, it is important to note that the correct implementation of the numerical grid is fundamental. Previous studies in the region (e.g., Carballo and Iglesias, 2013) have shown that high resolution models are needed in order to obtain a proper characterization of the coastal resource. The spatial resolution of these models should capture the sharp variations of the spectral parameters resulting from sudden modifications of the bathymetry; therefore, the size of the numerical grid depends on the bottom characteristics of the region of interest analysed.

After model propagation, the spectral parameters H_{m0}, T_e and θ_m are obtained at each grid node for the different deepwater energy bins propagated, and their wave power computed. Furthermore, despite the spectral wave parameters which define each bin being modified as waves leave the deepwater condition, the probability of occurrence of the corresponding conditions does not change. As a result, a vast amount of information is made available, which comprises the spectral parameters (H_{m0}, T_e, θ_m, J) and the occurrence of a certain number of wave cases (the same as energy bins considered) with a resolution of 0.5 m of H_{m0} and 0.5 of T_e, covering the whole area of interest analysed (at each node of the numerical grid). This information can be used to reconstruct the energy bins at any grid node following a similar procedure as described in the case of the deepwater dataset, or in other words, to obtain high resolution characterization matrices at any coastal location.

2. Methodology *cum* database implementation on the Galician coast

The methodology *cum* database developed in this thesis is applied to the Galician coast in Chapters III, IV and V, each chapter focusing on a particular aspect of its implementation so as to fully develop it for the characteristics of the Galician coast, as well as to provide the required information for implementing it to any other region of interest for wave energy exploitation.

In Chapter III – ***A high resolution geospatial database for wave energy exploitation***, the methodology is applied to a coastal region of major interest for wave energy exploitation, the Death Coast (delimited by Cape Finisterre and Cape Prior). For this purpose, the aforementioned procedure is implemented to this region by adjusting the parameters of the methodology to the specific characteristics of the region of interest. With this aim, the large deepwater dataset recorded by Vilán-Sisargas buoy is used, which covers a period of around 14 years (1998-2012) comprising a total number of approx. 100,000 hourly sea states.

In first place, a key aspect is the definition of the number of energy bins to be considered. With this aim, a resolution of 0.5 m of H_{m0} and 0.5 s of T_e is used following the methodology developed, together with intervals of 22.5º of θ_m which brings about an accurate description of the wave directionality in the region (Iglesias and Carballo, 2011b). A sensitivity analysis is then performed, showing the number or energy bins that should be considered if a certain level of energy (and time) is to be attained. This analysis shows that, instead of propagating a large amount of cases so as to consider 100% of the available energy, the consideration of the 787 most energetic energy bins is enough to achieve 95% of the total energy (corresponding to 88.7% of the time). Furthermore, the comparison of the omnidirectional characterization matrices at the deepwater site supplying 95% and 100% of energy evidences that the remaining 5% not considered is mostly composed of two types of sea states: (i) low power sea states due to reduced wave heights and periods (mostly sea states with less than 1 m of H_{m0}), and (ii) very high power sea states with very low occurrence (extreme conditions). Under both conditions, WECs do not usually operate; in the first case, they cannot operate due to the reduced wave height, and in the second case, WECs will be set in the so-called survival mode. This means that the most energetic wave conditions providing 95% of the total energy virtually represent 100% of the exploitable resource. On these grounds, the most energetic bins providing 95% of the total resource are retained.

The next step is to propagate the selected energy bins to the coastal area of interest. This is performed by using the spectral model SWAN (Simulating WAves Nearshore) (e.g., Akpinar and Kömürkü, 2012; Kim *et al*, 2011; Rusu and Guedes Soares, 2012b). After a thorough analysis of the bathymetry within the area of study and considering previous wave energy studies in the region (Iglesias and Carballo, 2009b, 2010b), the size of the numerical grid in the area of interest (of under 120 m depth, i.e., the maximum depth at which WECs are currently intended to operate) is set at 200 m (increasing towards the deepwater contours), which is estimated to provide an accurate resolution of the wave propagation process. This results in a total number of 69,847 grid nodes.

After running the model the relevant spectral parameters (H_{m0}, T_e, θ_m) are obtained at each node and the wave power, J, computed. This information, combined with the probability of occurrence of the different resulting energy bins, constitutes a set of data or database that can be used for reconstructing the wave energy resource at any site of interest in the form of a high resolution characterization matrix. In the present implementation, the probability of occurrence is computed in terms of annual figures, and thus, annual characterization matrices can be reconstructed.

The last step of this work is to develop a computer application, capable of accessing to the large amount of information stored, and automatically reconstructing the characterization matrix with the adequate resolution at any site throughout the Death Coast, so that any device developer, policy maker, researcher or stakeholder be able to compute the performance of any WEC-site combination of interest. With this in view, a set of MATLAB programmes are developed, which can access and manipulate the information resulting from the 787 numerical propagations at the 69,487 grid nodes (or locations). The result is the decision-aid tool **WEDGE (Wave Energy Diagram GEnerator)**, a computer application allowing the automatic reconstruction of the annual characterization matrix at any coastal location, for which the user only needs to interactively select the site of interest (resolution of 200 m), and define the required resolution of the bins (maximum of 0.5 m of H_{m0} and 0.5 s of T_e).

It is important to note that the energy bins of the characterization matrices generated by the tool correspond with a bivariate distribution of the H_{m0}, and T_e, in which the θ_m is neglected (omnidirectional matrix). This stems from the fact that the power matrices currently provided by device developers —with which the characterization matrices have to be combined so as to compute the energy production— are also omnidirectional. Nevertheless, the wave direction is taken into account throughout the development of the database; in particular, the numerical model computes the modification of the wave direction of each energy bin in their propagation from deepwater towards the coast, and the results are stored in the database together with the remaining spectral parameters. Thus, the user could use the database to generate trivariate characterization matrices, if the information related to the variation of the WEC's efficiency with the direction of waves was provided in the future.

The interest of this methodology *cum* database regarding the spatial resolution provided is further investigated in this chapter through a case study of a recently proposed wave farm in this coastal region. For this purpose, several wave characterization matrices are generated and compared: (i) a characterization matrix at the SIMAR point closest to the proposed area for the wave farm (the only wave resource dataset available prior to the present work), which is at a distance of more than 20 km, and (ii) the characterization matrices at three different locations within the proposed area, separated by less than 500 m. It is shown that high resolution spatial information in the order of that provided in this work —not available prior the present database— is required when conducting wave resource characterizations with a view to installing a wave farm in such regions as the Death Coast where large areas with irregular bottom contours are present.

On the other hand, as stated, to compute the WECs' performance in a coastal region with significant intra-annual resource variability on the basis of annual figures is likely to result in ill-informed decision making, thereby posing a threat to the economic viability of a wave farm project. With this in view in Chapter IV – ***Intra-annual wave resource characterization for energy exploitation: A new decision-aid tool***, the methodology developed is applied to the same region as in Chapter III, the Death Coast, but considering the intra-annual variation of the resource so as to generate a database providing the required information for reconstructing the resource in terms of intra-annual characterization matrices at any coastal location. For this purpose, the computation of the probability of occurrence of each deepwater trivariate energy bin should correspond with a period capable of capturing the temporal variability of the resource. In the present application, the monthly probability of occurrence of each bin is computed. As a result, after running the numerical model (with the same characteristics as those presented in Chapter III), the information made available consists of the spectral parameters of interest at each grid node, along with their monthly probability of occurrence. In the same way, the MATLAB-based tool is also modified so as to access and manipulate the dataset generated. This new decision-aid tool is called ***i*WEDGE (intra-annual Wave Energy Diagram GEnerator)**, allowing the computation of monthly characterization matrices throughout the Death Coast (200 m spaced) with a maximum resolution of 0.5 m of H_{mo} and 0.5 s of T_e.

The tool herein developed is applied to generate the monthly characterization matrices at a coastal location of special interest within the Death Coast, where a wave farm has been recently proposed. The results show that there exists a significant intra-annual variability in the energy resource which goes far beyond seasonal differences. Indeed, except in the months with lowest resource (June – August) significant monthly differences are observed (up to 40% within each season). This underlines the importance of considering the intra-annual and, in particular, the monthly variability when characterizing the wave energy resource in the Galician coast, insofar as it may greatly affect the performance of WECs.

Finally, in order to fully develop the methodology *cum* database presented in this thesis, a thorough analysis is conducted on the final output which is intended to make available as a result of its implementation: the power performance of different WEC-site combinations within a region of interest. With this aim, in Chapter V – ***The intra-annual variability in the performance of wave energy converters: A comparative study in N Galicia (Spain)***, the methodology *cum* database developed is implemented in the northern coastal region of Galicia (approx. delimited by Cape Prior and Ria de Ribadeo) so as to analyse the monthly power performance of various WECs at two coastal locations of interest (offshore and nearshore) where different wave farms have been previously proposed (Iglesias and Carballo, 2010b; Romillo, 2013). With this in view, the deepwater dataset provided by the Estaca de Bares buoy is used (hourly sea states covering the period 1996 – 2014), the resolution of the parameters defined in the previous implementations on the Death Coast retained (95% of level of energy with a resolution of 0.5 m of H_{m0}, 0.5 s of T_e and 22.5º of θ_m, for which in the present application 693 energy bins are selected) and the same spatial resolution of the numerical model as in previous implementations considered (200 m resulting in a total number of 69,969 grid points).

Then, the *i*WEDGE decision-aid tool is used to automatically compute the monthly characterization matrices at the locations of interest. It is observed that a significant intra-annual variability is present at both locations, going far beyond mere seasonal variations —in line with the results obtained in the implementation on the Death Coast in Chapter IV— consisting not only in large variations in the magnitude of the available resource, but also in strong variations in the energy distribution amongst bins.

The next step consists in combining the characterization matrices with the power matrices of various technologies, and computing their performance in terms of energy output, E_o, and capacity factor, C_f. The devices analysed are Pelamis, Oyster and B-HBA at the nearshore location and Pelamis, AWS and Aqua Buoy at the offshore location (Babarit *et al.*, 2012; Silva *et al.*, 2013). The large intra-annual variability in the available resource is reflected in significant variations in the performance of the WECs considered throughout the year. In effect, the results show that differences in the monthly energy output of more than 150% are apparent for all the technologies analysed, attaining 384% in the case of AWS between November and June at the offshore location. These variations in the energy output are reflected in similar variations in the capacity factor. In addition, important intra-annual differences are also apparent between both the technologies and locations considered. At the nearshore location, the greatest energy output is provided by B-HBA, with an average monthly output of 114.8 MWh; nevertheless, this device provides the lowest capacity factor with 0.058. In the case of the offshore site, AWS is the technology delivering the greatest energy output, with a monthly average output of 255.7 MWh, which again is that providing the lowest capacity factor with 0.143. Overall, the energy output at the offshore location is much greater than nearshore arising from the larger resource available; however, the results also point out that the efficiency of the different technologies also plays a major role in selecting the most appropriate technology, which results from the wave conditions significantly differing between locations. This is the case of the Pelamis which, as a result of its higher efficiency during powerful wave conditions, provides a low performance at the nearshore location but the highest figures at the offshore site —the technology with the highest capacity factor together with Aqua Buoy but with a greater energy output.

The results obtained underline the importance of considering the analysis conducted in this thesis by using the methodology *cum* database developed —the intra-annual performance of various WEC-site combinations— so as to select the most appropriate technology and location for installing a wave farm in a region.

VII

Conclusions

Conclusions

In this thesis a holistic methodology *cum* database for the exploitation of the wave energy resource in a coastal region is developed. In particular, its implementation provides the required information for reconstructing the available resource at any coastal site in terms high resolution characterization matrices (or energy diagrams) covering a period of interest (annual or intra-annual), or in other words, the elements required for computing the power performance of any WEC-site combination.

This methodology *cum* database, which involves the analysis of a large dataset of deepwater records together with high resolution numerical modelling, is implemented on the Galician coast and a computer application developed for easy accessing and manipulating the generated database. The resulting application constitutes a new decision-aid tool for wave energy exploitation called *i*WEDGE (intra-annual Wave Energy Diagram GEnerator), allowing the automatic reconstruction of the wave energy resource in terms of high resolution (maximum of 0.5 m of H_{m0} and 0.5 s of T_e) annual and monthly characterization matrices considering 95% of the total energy available —which is shown to virtually represent 100% of the exploitable resource— at any coastal location of interest (200 m spaced). Despite the characterization matrices generated being omnidirectional, the decision-aid tool developed could be used to produce trivariate directional characterization matrices insofar as wave direction information is taken into account throughout the development of the database, and the corresponding results stored together with the remaining spectral parameters.

Finally, the interest and functionality of the methodology *cum* database herein developed are analysed through different case studies of proposed wave farms within the Galician coast. The results obtained clearly indicate the importance of accurately computing the high resolution annual and intra-annual performance of different WEC-site combinations prior to installing a wave farm, thereby highlighting the interest of the present methodology *cum* database for an appropriate wave energy exploitation decision making within a coastal region of interest.

The present database and tool are currently available for the Galician coast; however, the same procedure could be used to generate similar information in any other coastal region of interest where long-term deepwater data are available. More specifically, in future work this database is expected to be extended so as to cover the entire Atlantic Region of Europe. It is worth mentioning that an intensive effort has been made over the last months in order to extend the functionalities of the present tool. In this regard, the power matrices of the current available technologies have been also incorporated to the database thereby allowing self-contained computation of the power performance of any WEC-site combination over the whole length of the Galician coast. Last but not least, in addition to the performance of WECs, the final decision making regarding the installation of a wave farm in a region should be based on the analysis of such environmental and socioeconomic aspects as protected areas, fishing activity, shellfish zones or shipping routes, amongst others, leading to an effective integrated coastal management. With this in view, the present database and tool have been extended so as to incorporate a geographical information system providing the spatial distribution of different environmental and socioeconomic data affecting wave energy exploitation, which are automatically taken into account by the tool in the decision-making process. These new functionalities are available under a brand new, user-friendly interface whose main features will be made publicly available online and through specialist scientific conferences and peer-reviewed journals.

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Appendix

Extended abstract (in Spanish)

La energía del oleaje ha mostrado ser una de las energías renovables con mayor potencial, con capacidad para reemplazar parte de la generación energética a partir de combustibles fósiles (Bahaj, 2012). Para que este potencial pueda ser aprovechado, es preciso disponer de dispositivos convertidores del oleaje (WECs, *wave energy converters*) eficientes y fiables. Como resultado de la intensa investigación llevada a cabo durante los últimos años para desarrollar WECs (Babarit *et al.*, 2012; Falcão, 2010), el aprovechamiento de este forma de energía está próximo a ser viable comercialmente.

La instalación adecuada de una planta de aprovechamiento undimotriz en una determinada región costera requiere el análisis y definición de ciertos aspectos, entre los cuales la selección combinada de la tecnología y ubicación más adecuadas es fundamental. A lo largo de los últimos años, se han llevado a cabo numerosas evaluaciones del recurso existente en diversas regiones con el fin de instalar una planta undimotriz (e.g., Akpinar and Kömürcü, 2012; Iglesias and Carballo, 2010a; Lenee-Bluhm *et al.*, 2011; Rusu and Guedes Soares, 2012a; Smith et al., 2013), centrándose en su gran mayoría en la determinación de condiciones del oleaje medias y extremales, así como en la identificación de *hot spots* o en la caracterización de detalle del recurso en localizaciones específicas. De este modo, se ha hecho disponible una gran cantidad de información del recurso energético del oleaje en las regiones costeras con mayor potencial; sin embargo, a pesar de su interés, esta información no proporciona los elementos necesarios para una selección combinada WEC-ubicación dentro de una determinada zona costera, o en otras palabras, no permite una toma de decisiones adecuada para el aprovechamiento de la energía del oleaje. Para ello, es necesario tener presente en todo momento cuál el objetivo final de una caracterización del recurso energético del oleaje con vistas a la instalación de una planta de aprovechamiento undimotriz: proporcionar los elementos necesarios para la estimación fiable de la producción y rendimiento de diferentes WECs en diversas ubicaciones de interés en una determinada región costera, que a su vez resulta de la necesidad de comparar diferentes combinaciones WEC-ubicación y con base en esto (i) definir la tecnología o tecnologías con mayor rendimiento en una localización determinada, e (ii) identificar la localización o localizaciones dentro de una región costera en las que una tecnología dada posee un mayor rendimiento.

La determinación de la producción y rendimiento energéticos de un convertidor de energía del oleaje en una determinada localización costera implica dos tareas fundamentales: (i) la caracterización del recurso en la ubicación en cuestión, y (ii) el cálculo de la producción y, con base en ella, de otros parámetros de rendimiento. Desafortunadamente, estas tareas son vistas generalmente como independientes, e implementadas de tal modo en las caracterizaciones de recurso; no obstante, están profundamente interrelacionadas debiendo ser tratadas como dos fases de un mismo proceso. Como consecuencia, la forma en la cual se han llevado a cabo la mayor parte de las caracterizaciones energéticas del oleaje durante los últimos años provoca que en la actualidad los elementos necesarios para llevar a cabo esta estimación no estén disponibles.

Esta limitación surge del hecho de que el rendimiento de los WECs depende en gran medida del clima marítimo existente en una determinada ubicación, y que a su vez se deriva de que su eficiencia —expresada por su matriz de potencia en términos de potencia de salida o de porcentaje sobre el total de la energía disponible— varía significativamente con las condiciones de oleaje. Por lo tanto, si se pretende realizar cálculos precisos de rendimiento, el recurso en una ubicación de interés específica debe ser descrito a través de una matriz de caracterización (o diagrama de energía), que determine la energía disponible y ocurrencia de las diferentes condiciones de oleaje existentes, definidas por medio de intervalos de energía o combinaciones de los principales parámetros del oleaje. De este modo, la producción energética de un dispositivo dado en un lugar de interés es el resultado de combinar la matriz de potencia del dispositivo con la matriz de caracterización de la localización. Para ello, las matrices de caracterización deben ser determinadas siguiendo procedimientos específicos (Carballo and Iglesias, 2012; Henriques *et al.*, 2013) que difieren en gran medida de los convencionales, diseñados para cubrir un porcentaje significativo del total del recurso energético disponible y obtener un nivel específico de resolución en la caracterización de los parámetros del oleaje (el mismo que el de la matriz de potencia de los dispositivos). Además, el recurso energético del oleaje puede sufrir variaciones importantes en distancias reducidas dentro de una determinada región costera (e.g., Iglesias and Carballo, 2009b), lo que significa que la tecnología que proporciona un mayor rendimiento puede variar dependiendo de la localización dentro del área costera considerada. En consecuencia, una caracterización del recurso con vistas a instalar una planta de aprovechamiento undimotriz debe permitir el cálculo con precisión de la matriz de caracterización del recurso en cualquier ubicación de interés dentro de una determinada región, y de este modo, la estimación del rendimiento de cualquier combinación WEC-ubicación.

Por otra parte, las regiones con mayor potencial energético del oleaje presentan normalmente una importante variabilidad intraanual del recurso (e.g., Neill and Hashemi, 2013; Sierra *et al.*, 2013), lo que a su vez puede resultar en una variación intraanual significativa en el rendimiento de los WECs. De este modo, en estas regiones es preciso obtener matrices de caracterización del recurso que cubran períodos de tiempo (e.g., mensuales, estacionales, etc.) que reflejen la variabilidad temporal del recurso. No obstante, puesto que los análisis de recurso convencionales se centran normalmente en valores medios o extremales, la información necesaria para generar dichas matrices está disponible únicamente en un número limitado de localizaciones, normalmente aquellas en donde una boya ha estado en operación durante períodos extensos.

En esta tesis se desarrolla una metodología holística cuya implementación en una determinada región costera genera un conjunto de datos que permita el cálculo preciso de la producción y rendimiento energéticos de cualquier combinación WEC-ubicación, en base al cual se pueda llevar a cabo una toma de decisiones adecuada para instalar una planta de aprovechamiento energético undimotriz. Para ello, la metodología *cum* base de datos se implementa en la costa gallega, desarrollándose la herramienta de ayuda a la toma de decisiones basada en MATLAB ***i*****WEDGE** (intra-annual Wave Energy Diagram GEnerator), que permite acceder y manipular de forma sencilla la información generada, de modo que se pueden reconstruir de forma automática matrices de caracterización anual e intraanual de alta resolución en cualquier ubicación costera, y de este modo determinar la producción y rendimiento energéticos de cualquier combinación WEC-ubicación.

Esta tesis se estructura en siete capítulos, de los cuales los Capítulos III, IV y V corresponden con sendas publicaciones en revistas científicas y constituyen el cuerpo principal de la tesis. En primer lugar, en el Capítulo I – *Introduction*, se proporciona una perspectiva general al presente trabajo, y seguidamente, en el Capítulo II – *Objectives*, se indican los objetivos final e intermedios que se pretenden alcanzar. A continuación, en los Capítulos III – *A high resolution geospatial database for wave energy exploitation*, publicado en *Energy*, IV – *Intra-annual wave resource characterization for energy exploitation: A new decision-aid* *tool*, publicado en *Energy Conversion and Management* y V – *The intra-annual variability in the performance of wave energy converters: A comparative study in N Galicia (Spain)*, también publicado en *Energy*, se expone de forma detallada la metodología propuesta y se implementa en diferentes zonas costeras de Galicia, abordándose en cada uno de ellos diferentes aspectos específicos y fundamentales para la consecución del objetivo final de este trabajo. El Capítulo VI – *General Discussion*, contiene una discusión general común a la tesis, y finalmente, en el Capítulo VII – *Conclusions*, se presentan las principales conclusiones obtenidas así como las futuras líneas de investigación a desarrollar.

A continuación se presenta de forma sintética la metodología propuesta, se resumen los aspectos abordados, así como los resultados y principales conclusiones obtenidas.

La metodología *cum* base de datos desarrollada en esta tesis consta de tres fases principales: (i) la selección de los intervalos de energía que proporcionan la mayor parte de la energía disponible en aguas profundas, basándose para ello en registros de boyas; (ii) la propagación de los intervalos de energía por medio de modelización numérica espectral; (iii) la reconstrucción de los intervalos de energía en cualquier ubicación de la región costera de interés.

La primera fase de la metodología consiste en seleccionar los intervalos de energía en una ubicación dentro de la región costera de interés en la cual esté disponible un conjunto extenso de registros de estados de mar en aguas profundas. Con este fin, el recurso en aguas profundas se caracteriza por medio de la probabilidad de ocurrencia de intervalos de energía trivariados de altura de ola significante, H_{m0}, período energético, T_e, y dirección media, θ_m. Un aspecto clave para realizar una caracterización precisa del recurso es la selección del tamaño adecuado de los intervalos. Actualmente la eficiencia de los WECs es proporcionada por los desarrolladores de tecnología como función de la H_{m0} y el T_e, asumiendo que ésta no varía con la dirección del oleaje. Por tanto, la producción energética de un dispositivo en una localización costera resulta de combinar la matriz de potencia de la tecnología seleccionada con la matriz de caracterización omnidireccional del recurso en la localización de interés con un mismo nivel de resolución (tamaño de los intervalos de energía). De este modo, el tamaño de los intervalos de energía de H_{m0} y T_e en aguas profundas —que serán propagados posteriormente con el fin de reconstruir las matrices de caracterización a lo largo de la costa— deberán tener el mismo nivel de resolución que los de la matriz de potencia del WEC de interés. Con base en las matrices de potencia actualmente disponibles (Babarit *et al.*, 2012; Silva *et al.*, 2013; The Carbon Trust, 2010), la resolución de los intervalos de H_{m0} y

T_e se establece en 0.5 m y 0.5 s, respectivamente, que se corresponde con la resolución más elevada actualmente proporcionada por los desarrolladores de tecnología. En cuanto a la θ_m, cuya información es necesaria para transferir la energía del oleaje desde aguas profundas hacia la costa, su resolución debe permitir capturar la direccionalidad del recurso, la cual a su vez varía en gran medida de acuerdo con las características de la región considerada (e.g., Iglesias and Carballo, 2009b).

Una vez definida la resolución de los intervalos de energía en aguas profundas, cada estado de mar registrado se asigna a su correspondiente intervalo trivariado, se calcula su potencia, J, y se determina la energía total que proporciona cada intervalo, E_b, de acuerdo con su probabilidad de ocurrencia, O_b. Finalmente, se seleccionan los intervalos que contribuyen con la mayor parte de la energía disponible para ser propagados posteriormente hacia la costa a través de técnicas de modelización numérica espectral. De acuerdo con el procedimiento convencional habitualmente se considera un conjunto de casos de estudio reducido; sin embargo, investigaciones recientes señalan la importancia de considerar un elevado porcentaje del total de la energía disponible (90-95%) (Iglesias and Carballo, 2011b), resultando en una caracterización del recurso de mayor detalle y, en consecuencia, en estimaciones más precisas del rendimiento de los WECs en la ubicaciones de interés. En la práctica, esto requiere la consideración de un número de intervalos de energía más elevado, lo que significa la propagación de un mayor número de condiciones del oleaje y, por tanto, un mayor esfuerzo computacional. En este sentido, la selección de los intervalos de energía debe realizarse en base al total de energía proporcionado por cada intervalo, permitiendo así considerar un mayor porcentaje del total de energía disponible para un mismo número de casos considerados, i.e., una mayor precisión en los resultados obtenidos con un mismo esfuerzo computacional.

La siguiente fase de la metodología consiste en transferir el recurso en aguas profundas hacia el área costera de interés. Con este fin, los intervalos de energía seleccionados son propagados a través de técnicas de modelización numérica espectral, considerando cada una de ellos como un caso de oleaje definido por los parámetros espectrales (H_{m0}, T_e, θ_m) que mejor representan las condiciones de oleaje dentro del intervalo —aquellos que proporcionan el valor medio de energía—. Para ello, es importante tener en consideración que la correcta implementación de la malla numérica es un aspecto fundamental. En este sentido, estudios previos en la costa gallega (e.g., Carballo and Iglesias, 2013) han mostrado que es preciso implementar modelos de alta resolución para así obtener caracterizaciones adecuadas del recurso. La resolución espacial de estos modelos debe ser capaz de capturar las variaciones abruptas que pueden experimentar los parámetros espectrales como consecuencia de modificaciones repentinas en la configuración batimétrica; por tanto, el tamaño de la malla numérica es altamente dependiente de las características del fondo de la región de interés analizada.

Finalmente, una vez realizada la propagación numérica, se obtienen los parámetros espectrales resultantes (H_{m0}, T_e, θ_m) en cada nodo de la malla computacional para los diferentes intervalos de energía en aguas profundas propagados, y se calcula su potencia, J. Además, a pesar de que los parámetros espectrales que definen cada intervalo de energía se modifican a medida que el oleaje se propaga hacia la costa (una vez abandonada la condición de aguas profundas), la probabilidad de ocurrencia de las condiciones resultantes no varía. De este modo, se hace disponible una gran cantidad de información formada por los principales parámetros espectrales (H_{m0}, T_e, θ_m, J) y la ocurrencia de un determinado número de casos de oleaje (el mismo que de intervalos de energía considerados) con una resolución de 0.5 m de H_{m0} y 0.5 de T_e, cubriendo toda el área de interés analizada (en cada nodo de la malla numérica). Esta información puede ser empleada, por tanto, para reconstruir los intervalos de energía en cada nodo de la malla computacional, siguiendo para ello un proceso similar al descrito en el caso del conjunto de datos en aguas profundas, o en otras palabras, para obtener matrices de caracterización de alta resolución en cualquier ubicación costera.

La metodología presentada se implementa en la costa gallega en los Capítulos III, IV y V, cada uno de ellos enfocándose en un aspecto específico de su implementación, de modo que ésta pueda desarrollarse en su totalidad para las características de la costa gallega, así como proporcionar la información necesaria para poder aplicarla en cualquier otra región de interés para el aprovechamiento energético del oleaje.

En el Capítulo III – ***A high resolution geospatial database for wave energy exploitation***, la metodología se aplica en una región costera de gran interés para el aprovechamiento energético del oleaje, A Costa da Morte (*Death Coast*) (delimitada por el Cabo Finisterre y el Cabo Prior), ajustándose para ello diversos parámetros del procedimiento establecido en función de las características específicas de la región. Con este fin, se emplea el extenso conjunto de datos proporcionado por la boya de Vilán-Sisargas que cubre un período de en torno a 14 años (1998 – 2012) de registros de estados de mar en aguas profundas de una hora de duración.

En primer lugar, un aspecto clave es la definición del número de intervalos de energía que es preciso considerar. Para ello, se emplea una resolución de 0.5 m de H_{m0} y 0.5 s de T_e, de acuerdo la metodología definida, conjuntamente con intervalos de 22.5º de θ_m, que proporcionan una descripción precisa de la direccionalidad del oleaje en la región (Iglesias and Carballo, 2011b). A continuación, se realiza un análisis de sensibilidad para poder determinar el número de intervalos de energía que es preciso considerar para alcanzar un nivel de energía (y tiempo) específico. Este análisis muestra que, en lugar de tener en cuenta la totalidad de intervalos para así considerar el 100% de la energía disponible, la selección de los 787 intervalos más energéticos permite alcanzar el 95% del total de la energía (que se corresponde con el 88.7% del tiempo).

Además, la comparación de las matrices de caracterización omnidireccionales en aguas profundas correspondientes al 95% y 100% de la energía muestra que el restante 5% no considerado está formado fundamentalmente por dos tipos de estados de mar: (i) estados de poca potencia debido a reducidas alturas de ola (y períodos) (principalmente estados de mar de menos de 1 m de H_{m0}), y (ii) estados de potencia muy elevada pero con poca ocurrencia (situaciones extremales). Durante ambas condiciones, los WECs normalmente no operan; en el primer caso, los dispositivos no pueden entrar en funcionamiento debido a la reducida altura de ola existente, y en el segundo caso, se sitúan en el denominado modo de supervivencia. Esto significa que las condiciones más energéticas que proporcionan el 95% del total de la energía representan virtualmente el 100% del recurso explotable. Con base en esto se seleccionan los intervalos más energéticos correspondientes al 95% del total del recurso disponible.

El siguiente paso consiste en propagar los intervalos de energía seleccionados a la zona costera de interés para lo cual se emplea el modelo espectral SWAN (Simulating WAves Nearshore) (e.g., Akpinar and Kömürkü, 2012; Kim *et al*, 2011; Rusu and Guedes Soares, 2012b). Después de un análisis exhaustivo de la batimetría dentro de la zona de estudio y teniendo en consideración estudios energéticos del oleaje previos (Iglesias and Carballo, 2009b, 2010b), el tamaño de la malla numérica en el área de interés (zona costera con una profundidad inferior a 120 m, que se corresponde con la máxima profundidad a la que actualmente operan los WECs) se establece en 200 m (incrementándose progresivamente hacia el contorno de aguas profundas), el cual se estima que proporciona una resolución adecuada para el estudio de los procesos de propagación del oleaje, resultando en un número total de 69,847 nodos.

Una vez propagados numéricamente los intervalos de energía seleccionados, se obtienen los parámetros espectrales relevantes (H_{m0}, T_e, θ_m) en cada nodo y se determina su potencia, J. Esta información, combinada con la probabilidad de ocurrencia de los intervalos de energía resultantes, constituye un conjunto de datos o base de datos que puede ser empleada para reconstruir el recurso energético del oleaje en cualquier ubicación de interés en forma de una matriz de caracterización de alta resolución. En la presente implementación, la probabilidad de ocurrencia se calcula en términos anuales y, por lo tanto, se pueden reconstruir matrices de caracterización anual.

El último paso de este trabajo consiste en desarrollar una herramienta informática capaz de acceder a la extensa información almacenada y reconstruir de forma automática la matriz de caracterización con la resolución necesaria en cualquier ubicación de la región de A Costa da Morte, de modo que se puedan obtener la producción y rendimiento energéticos de cualquier combinación WEC-ubicación de interés. Con este fin, se desarrollan un conjunto de programas en MATLAB capaces de acceder y manipular la información resultante de las 787 propagaciones numéricas en los 69,487 nodos de la malla computacional. El resultado es una herramienta informática denominada WEDGE (Wave Energy Diagram GEnerator) que permite la reconstrucción automática de la matriz de caracterización anual en cualquier localización costera (resolución de 200 m), para lo cual el usuario únicamente precisa seleccionar de forma interactiva la ubicación de interés y definir la resolución requerida de los intervalos (máximo de 0.5 m de H_{m0} y 0.5 s de T_e).

Es importante tener presente que los intervalos de energía de las matrices de caracterización generadas por la herramienta se corresponden con un distribución bivariada de la H_{m0} y el T_e, en la cual la θ_m es omitida (matriz omnidireccional). Esto se debe a que las matrices de potencia que en la actualidad proporcionan los desarrolladores de tecnología —con las cuales se tienen que combinar las matrices de caracterización para calcular la energía generada— son también omnidireccionales. Sin embargo, la dirección del oleaje se tiene en consideración a través de todo el desarrollo de la base de datos; en particular, el modelo numérico calcula la modificación de la dirección del oleaje de cada intervalo de energía en su propagación desde aguas profundas hacia la costa, y los resultados se almacenan en la base de datos conjuntamente con los restantes parámetros espectrales. Por lo tanto, la presente herramienta se podría emplear para generar matrices de caracterización direccionales (trivariadas), en el caso de que en el futuro se proporcione la información relativa a la variación de la eficiencia de los dispositivos en función de la dirección del oleaje.

Por último, en este capítulo se investiga el interés de la presente metodología *cum* base de datos en relación a la resolución espacial proporcionada a través de un caso de estudio de una planta de aprovechamiento energético undimotriz propuesta recientemente en la región. Para ello, se generan y comparan diferentes matrices de caracterización: (i) una matriz de caracterización correspondiente al Punto SIMAR más cercano al área propuesta para la planta (el único conjunto de datos disponible con anterioridad al presente trabajo), el cual está situado a una distancia de más de 20 km, y (ii) las matrices de caracterización en tres localizaciones diferentes dentro del área propuesta, separadas por menos de 500 m. Las diferencias significativas obtenidas entre las matrices evidencian que para una adecuada caracterización del recurso energético del oleaje con vistas a la instalación de una planta de aprovechamiento undimotriz en regiones costeras como A Costa da Morte, en donde existen extensas áreas con batimetría irregular, es preciso reconstruir matrices de caracterización con una resolución espacial elevada, del orden a la proporcionada a través de este trabajo —información no disponible con anterioridad al desarrollo de la presente base de datos.

Por otra parte, tal y como se comentó previamente, la determinación del rendimiento de los WECs en una región costera que presenta una variabilidad intraanual significativa del recurso en base únicamente a datos anuales puede resultar en una toma de decisiones errónea. Por ello, en el Capítulo IV – ***Intra-annual wave resource characterization for energy exploitation: A new decision-aid tool***, la metodología desarrollada se aplica a la misma región que en el Capítulo III, A Costa da Morte, pero considerando la variación intraanual del recurso y así poder generar una base de datos que proporcione la información necesaria para reconstruir el recurso en términos de matrices de caracterización intraanual en cualquier ubicación costera.

Con este fin, el análisis de la probabilidad de ocurrencia de cada intervalo de energía trivariado en aguas profundas debe realizarse para períodos capaces de capturar la variabilidad temporal del recurso, considerándose en la presente aplicación su probabilidad de ocurrencia mensual. De este modo, una vez propagados los intervalos seleccionados por medio de técnicas de modelización numérica (con las mismas características que las presentadas en el Capítulo III), la información que se obtiene para los diferentes casos de estudio está formada, además de por los parámetros espectrales de interés en cada nodo de la malla, por su probabilidad de ocurrencia mensual (permanece invariada a través del proceso de propagación). De modo similar, la herramienta basada en MATLAB se modifica con el fin de poder acceder y manipular el nuevo conjunto de datos generado. Esta nueva herramienta de toma de decisiones se denomina ***i*WEDGE** (intra-annual Wave Energy Diagram GEnerator), que permite la reconstrucción de matrices de caracterización mensual a lo largo de toda A Costa da Morte (cada 200 m) con una resolución máxima de 0.5 m de H_{mo} y 0.5 s de T_e.

Finalmente, la herramienta desarrollada se aplica en una localización de especial interés en A Coste da Morte, en donde se ha propuesto recientemente la instalación de una planta undimotriz. Los resultados muestran que existe una variabilidad intraanual elevada durante períodos inferiores a los estacionales. De hecho, con excepción de los meses con recurso más reducido (Junio – Agosto) se observan diferencias mensuales significativas (hasta un 40% dentro de cada estación). Esto hace hincapié en la importancia de considerar la variabilidad intraanual y, en particular, las variaciones mensuales, a la hora de caracterizar el recurso energético del oleaje en la costa gallega (así como en zonas costeras con características similares), dado que puede afectar en gran medida al rendimiento de los WECs.

Para poder desarrollar completamente la metodología *cum* base de datos presentada en esta tesis, es preciso llevar a cabo un análisis exhaustivo de la información final que se pretende hacer disponible a través de su implementación: el rendimiento de diferentes combinaciones WEC-ubicación dentro de una determinada región costera de interés. Con este fin, en el Capítulo V – ***The intra-annual variability in the performance of wave energy converters: A comparative study in N Galicia (Spain)***, la metodología *cum* base de datos se implementa en la región costera del norte de Galicia, (aproximadamente delimitada por el Cabo Prior y la Ría de Ribadeo) con el fin de analizar el rendimiento mensual de varios WECs en dos localizaciones costeras de interés, una próxima a la costa (*nearshore*) y otra alejada de la costa (*offshore*), en donde diversas plantas de aprovechamiento undimotriz han sido propuestas recientemente (Iglesias and Carballo, 2010b; Romillo, 2013). Con este fin, se recurre al conjunto de datos proporcionado por la boya de Estaca de Bares que dispone de registros de estados de mar horarios en aguas profundas durante aproximadamente 18 años (1996 – 2014), y se consideran los parámetros definidos en las implementaciones previas en A Costa da Morte (95% de nivel de energía con una resolución de 0.5 m de H_{m0}, 0.5 s de T_e y 22.5º of θ_m, para lo cual en la presente aplicación se seleccionan 693 intervalos de energía), así como la misma resolución espacial para el modelo numérico de propagación del oleaje (200 m en el área de interés que resulta en un total de 69,969 nodos).

A continuación, se emplea la herramienta de toma de decisiones *i*WEDGE para reconstruir las matrices de caracterización mensual en las localizaciones de interés. Se observa que existe una variabilidad intraanual significativa en ambas ubicaciones que va más allá de simples variaciones estacionales —en concordancia con los resultados obtenidos en la implementación en A Costa da Morte en el Capítulo IV—, y que consiste no sólo en importantes diferencias en la magnitud del recurso disponible, sino también en variaciones significativas en la distribución de energía entre intervalos.

El siguiente paso consiste en combinar las matrices de caracterización obtenidas con las matrices de potencia de diversas tecnologías, y calcular su rendimiento en términos de energía producida, E_o, y factor de capacidad, C_f. Los dispositivos analizados son Pelamis, Oyster y B-HBA en la localización *nearshore* y Pelamis, AWS y Aqua Buoy en la localización *offshore* (Babarit *et al.*, 2012; Silva *et al.*, 2013). La elevada variabilidad intraanual en el recurso disponible se ve reflejada en variaciones significativas a lo largo del año en el rendimiento de los WECs considerados. En efecto, los resultados muestran diferencias en la energía mensual producida de más del 150% para todas las tecnologías analizadas, alcanzado el 384% en el caso del AWS entre noviembre y junio en la localización *offshore*. Estas variaciones en la energía producida se ven reflejadas en variaciones similares en el factor de capacidad. Del mismo modo, también son evidentes importantes diferencias intraanuales tanto entre las tecnologías como entre las localizaciones consideradas. En la localización *nearshore* el dispositivo que proporciona una mayor producción energética es el B-HBA, con una producción mensual media de 114.8 MWh; no obstante, este dispositivo es el que presenta el factor de capacidad más reducido con 0.058. En el caso de la ubicación *offshore*, el AWS es la tecnología que proporciona la mayor producción energética, con una producción mensual media de 255.7 MWh, siendo del mismo modo el que posee un menor factor de capacidad con 0.143. En general, la energía generada en la localización *offshore* es considerablemente más elevada que en la localización *nearshore*, como consecuencia del mayor recurso disponible; sin embargo, los resultados señalan que la eficiencia de los diferentes dispositivos también juega un papel fundamental a la hora de seleccionar la tecnología más adecuada, y que a su vez se deriva de que las condiciones del oleaje difieren significativamente entre localizaciones. Este es sin duda el caso del Pelamis, el cual posee una mayor eficiencia para condiciones de oleaje de potencia elevada, presentando así un rendimiento reducido en la localización *nearshore* pero el rendimiento más elevado en la ubicación *offshore* —es la tecnología con el factor de capacidad más elevado conjuntamente con la tecnología Aqua Buoy pero con una mayor producción energética.

En conclusión, en la presente tesis se desarrolla una metodología holística para el aprovechamiento del recurso energético del oleaje dentro de una determinada región costera. En particular, su implementación permite generar la información necesaria para la reconstrucción de matrices de caracterización de alta resolución correspondientes a un determinado período temporal (anual o intraanual) en cualquier localización costera dentro de una región de interés, es decir, la información necesaria para llevar a cabo cálculos precisos de producción y rendimiento energéticos de cualquier combinación WEC-ubicación.

La implementación de esta metodología *cum* base de datos, que implica el análisis de un extenso conjunto de datos en aguas profundas conjuntamente con el empleo de modelización numérica de alta resolución, se aplica a la costa gallega desarrollándose una herramienta informática capaz de acceder y manipular de forma eficiente la base de datos generada. La herramienta resultante denominada *i*WEDGE (intra-annual Wave Energy Diagram GEnerator) constituye una herramienta de ayuda a la toma de decisiones, que permite la reconstrucción automática del recurso energético del oleaje en forma de matrices de caracterización anual y mensual de alta resolución (máximo de 0.5 m de H_{m0} y 0.5 s de T_e) considerando el 95% del total del recurso disponible —que se muestra que representa virtualmente el 100% del recuso explotable— en cualquier ubicación costera de interés (resolución espacial de 200 m).

Finalmente, el interés y funcionalidad de la metodología *cum* base de datos desarrollada a través de esta tesis son analizados por medio de diferentes casos de estudio de plantas de aprovechamiento energético undimotriz propuestas recientemente en la costa gallega. Los resultados obtenidos indican la importancia de calcular con precisión el rendimiento anual e intraanual de diferentes combinaciones WEC-ubicación para poder llevar a cabo una toma de decisiones adecuada a la hora de instalar una planta de aprovechamiento energético undimotriz en una región costera, para lo cual la implementación de la metodología *cum* base de datos desarrollada en esta tesis ha mostrado ser de gran interés.

La presente base de datos y herramienta informática están actualmente disponibles para la totalidad de la costa gallega; no obstante, el mismo procedimiento podría ser empleado para generar una información similar en cualquier otra región costera de interés en donde existan registros de oleaje extensos en aguas profundas. De modo más específico, en trabajos futuros se espera que esta base de datos se extienda a toda la región Atlántica de Europa. Es interesante mencionar que a lo largo de los últimos meses se ha realizado un intenso esfuerzo con el fin de aumentar las funcionalidades de la herramienta informática desarrollada. En este sentido, las matrices de potencia de los dispositivos actualmente existentes se han incorporado a la base de datos, permitiendo de este modo el cálculo automático a través de la propia herramienta del rendimiento de cualquier combinación WEC-ubicación a lo largo de toda la costa gallega. Por último, es preciso tener en consideración que además del rendimiento de los WECs, la decisión final relativa a la instalación de una planta de aprovechamiento energético undimotriz en una determinada región costera debe estar basada en el análisis de aspectos ambientales y socioeconómicos tales como áreas protegidas, actividad pesquera, zonas de marisqueo o rutas marítimas, entre otros, conduciendo así a una gestión integrada efectiva de la zona costera. Teniendo esto en consideración, la presente base de datos y herramienta se han extendido con el fin de incorporar un sistema de información geográfica que proporciona la distribución espacial de detalle de diversos aspectos ambientales y socioeconómicos que afectan a la explotación de la energía del oleaje, y que son tenidos en consideración por la herramienta en el proceso de toma de decisiones. Estas nuevas funcionalidades están disponibles bajo una interfaz intuitiva y novedosa cuyas características principales se harán públicas de forma *online* y a través de conferencias y revistas científicas.